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THE STRUCTURE AND GROWTH OF VIRGIN BEECH-BIRCH-MAPLE-HEMLOCK FORESTS IN NORTHERN PENNSYLVANIA [1]

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INTRODUCTION

Of the virgin beech-birch-maple-hemlock forests which formerly occupied large sections of northern Pennsylvania and southern New York only remnants now remain. The better known of these in Pennsylvania, namely, Hearts Content, the Tionesta Tract, Cook Forest, and the Ganoga Glen area of the Ricketts estate, have been or are being set aside as parks and scenic areas for public recreational use, and as laboratories for the scientific study of the composition and structure of this forest type. A number of investigators have studied the composition of the Hearts Content, Tionesta, and Cook Forests (*4*, *9*, *13*) [2] as well as the general ecological relationships of this forest type (*5*, *6*). The discovery of several additional virgin stands in Bradford and Sullivan Counties and a knowledge of the virgin forest tracts owned by the Central Pennsylvania Lumber Company near Sheffield, Warren County, led the writers to undertake an investigation of the structure and growth of virgin forests of this type, since data of this sort supply the forester with basic information in the management of uneven-aged stands. Further, it was the desire of the writers to obtain field data of the smaller Bradford and Sullivan County tracts and the Central Pennsylvania Lumber Company holdings before they were logged off. Stand tables of such tracts are irreplaceable and are a valuable source of information for further comparative studies of the virgin forest.

The structure of forest stands has to do both with composition and with diameter distribution. Meyer (*12*), Schnur (*15*), and others investigated diameter distributions in even-aged stands. They employed statistical methods to produce harmonized stand tables for each tree species. Such an application is of value in the construction of yield tables. Diameter distributions in uneven-aged forests have been studied especially by de Liocourt (*8*) and Schaeffer, Gazin, and d'Alverny (*14*) in France. The latter applied the well known graphical J-shaped distribution curve for uneven-aged forest stands to the management of selection forests. More recently diameter distributions of selection forests in Switzerland have been represented by an exponential function. This method was also applied to virgin forests in Mexico (*10*, *11*). Hough (*3*) found that diameter distributions of virgin forests in northwestern Pennsylvania show trends similar in form to managed selection forests in Europe.

[1] Received for publication July 28, 1942.

[2] Italic numbers in parentheses refer to Literature Cited, p. 483.

The application of the results of this study will not be discussed in this paper. It might be pointed out, however, that a knowledge of the balanced structure of an uneven-aged forest is of great importance for practical management. Failure to take into account the desired normal structure of a forest, a structure which should be secured and maintained in order to achieve the goal of sustained-yield management, often leads to a gradual depletion of the growing stock. Data derived from a study of the structure of virgin forests represent a valuable basis for an appraisal of the normal growing stock of uneven-aged forests. Such data should be secured before the last remnants of virgin stands in many sections of the country disappear forever.

EXPERIMENTAL MATERIAL

The location and a general description of the virgin stands included in this study are given in table 1. The stand tables have been compiled and published in the form of a mimeographed research note [3] in order to be available for future reference. In table 2 are listed some of the more important characteristics for each stand which can be numerically evaluated. A total of 419.2 acres of virgin stands were calipered. The distribution of volume by diameter groups (small, medium, and large timber) varies considerably, though each stand shows what is called a balanced distribution of number of trees by diameter classes. It is apparent that the volume distribution by diameter groups follows a certain pattern, but only through a systematic analysis will it be possible to elucidate this variation in the structure of the virgin forests studied.

In computing the cubic foot volume of the various stands one common volume table was applied to all species. A preliminary examination of volume per tree and by species revealed no significant difference between the volumes at different localities, or between the various species of hardwoods. A common volume table for all hardwoods and one volume table for hemlock was then established. It so happened that these two volume tables in turn showed no significant difference; one common volume table was therefore established for all species, as shown in table 3. In spite of the fact that the differences between the various volume tables originally established were statistically not significant, it must be admitted that larger samples of height measurements would probably have shown that some of the observed differences between certain species and localities actuallyare significant. However, for the comparison of the structure of the various virgin stands in terms of cubic feet it is decidedly an advantage to apply one and the same volume table to all species and all stands, since the results of the data from the various stands can then be compared more easily. It should also be said that the yield from cuttings made in these stands would hardly coincide in all cases with the anticipated cubic foot volume per tree, since the actual degree of utilization varies quite widely from one operation to another.

[3] YOUORSKI, J., and MEYER, H. A. STAND TABLES OF VIRGIN BEECH-BIRCH-MAPLE-HEMLOCK FORESTS. Pa. State Forest School Res. Paper 3. 1942. [Processed.]

TABLE 1.—*General description of virgin stands included in study*

Designation of tract and location	Stand No.	Area	Location and description
		Acres	
McClure: I	1	12.2	In Bradford County; isolated farm woodland.
Hess:			
I	2	14.4	In Sullivan County; farm woodland, rocky site with northern aspect.
II	3	10.8	
Ricketts:			
III	4	9.4	On Wyoming and Luzerne County line in bottom land along Kitchen Creek.
IV	5	5.0	
Rightmeier:			
I and II	6	11.7	In Sullivan County; farm woodland along creek and on gentle slope, deep soil.
III	7	17.6	
IV	8	13.5	
V	9	22.1	
VI	10	9.7	
C. P. L. Larson:			
I	11	34.6	In Warren County; on upland site with western aspect.
II	12	7.4	
C. P. L. Dunham:			
I	13	36.9	
II	14	21.5	In Warren County; on moderate to steep slope with eastern aspect.
III	15	15.3	
IV	16	32.3	
Tionesta:			
II	17	12.5	In scenic area of Tionesta forest along both sides of Cherry Creek, mostly deep and wet soils.
III	18	11.2	
IV-A	19	15.4	
IV-B	20	14.6	
V	21	10.6	
VI	22	14.3	
VII	23	21.4	
VIII	24	9.2	
IX	25	24.2	
X	26	11.4	

TABLE 2.—*Numerical characteristics of individual stands, material 7 inches and over*

Stand No.	Area [1]	Trees per acre	Volume per acre	Distribution of volume by diameter groups (inches)			a [2]	k [2]	b [2]	Proportion of hemlock stems
				7 to 13	13 to 21	21 and over				
	Acres	*Number*	*Cubic feet*	*Percent*	*Percent*	*Percent*				*Percent*
1	12.2	86.1	3,072	28	33	39	0.143	33	31	20
2	14.4	89.2	4,130	18	37	45	.114	24	33	11
3	10.8	78.3	4,171	13	41	46	.072	12	31	6
4	9.4	89.4	3,097	27	45	28	.175	53	35	14
5	5.0	97.6	5,313	14	31	55	.088	18	33	45
6	11.7	98.4	3,699	25	41	34	.145	41	31	25
7	17.6	113.6	4,226	25	44	31	.145	47	31	25
8	13.5	103.2	3,910	24	40	36	.140	40	31	21
9	22.1	92.0	3,862	20	44	36	.122	28	31	14
10	9.7	63.4	2,156	29	45	26	.180	41	33	21
11	34.6	77.8	4,681	12	29	59	.071	11	33	46
12	7.4	101.4	5,314	15	38	47	.079	17	31	45
13	36.9	66.9	4,331	11	29	60	.073	10	35	54
14	21.5	56.9	3,427	11	35	54	.085	10	35	33
15	15.3	65.7	2,742	21	34	45	.135	23	35	32
16	32.3	74.0	3,593	17	27	56	.116	19	37	51
17	12.5	66.8	3,110	17	41	42	.150	30	41	24
18	11.2	73.3	3,544	17	33	50	.137	27	39	40
19	15.4	94.2	4,508	19	29	53	.131	31	39	33
20	14.6	84.7	5,356	11	24	65	.092	15	39	50
21	10.6	82.1	4,928	13	26	61	.102	18	39	41
22	14.3	75.4	5,040	11	22	67	.083	12	39	38
23	21.4	81.1	4,054	16	34	50	.128	26	39	25
24	9.2	88.5	5,057	16	23	61	.103	19	39	27
25	24.2	86.3	4,293	15	33	52	.134	31	41	26
26	11.4	72.3	4,733	12	33	55	.118	20	41	38

[1] Total, 419.2 acres.
[2] See text for further explanation of these coefficients.

TABLE 3.—*Common local cubic foot volume table* [1]

Diameter at breast height (inches)	Volume [2]	Diameter at breast height (inches)	Volume [2]
	Cubic feet		*Cubic feet*
8	9.315	30	214.3
10	15.83	32	249.9
12	24.38	34	288.4
14	35.14	36	330.3
16	48.23	38	375.5
18	63.78	40	424.1
20	81.90	42	476.1
22	102.7	44	531.6
24	126.2	46	590.8
26	152.6	48	653.5
28	182.0	50	720.0

[1] Logarithmic volume equation: $\log V = -1.1733 + 2.3724 \log D$.
[2] Includes stump and bark, but no limb wood.

The finally accepted local cubic foot volume table was plotted on logarithmic paper and a straight line was fitted to the points. The constants a and b of the logarithmic volume equation $\log V = a + b \log D$ are given in table 3.

THE STRUCTURE OF THE VIRGIN FOREST

DISTRIBUTION OF NUMBER OF TREES BY DIAMETER CLASSES

A virgin forest or a virgin stand capable of maintaining its volume must show a balanced distribution of number of trees by diameter classes. The actual growing stock of a forest can be maintained only if the trees which are dying every year are continuously being replaced by trees moving up from the lower diameter classes. It is therefore necessary that the number of trees in successive diameter classes decrease gradually with increasing diameters. In making this statement it is assumed that diameter increment is a slow-changing function of diameter at breast height, which is known to be true. An example of a well-balanced diameter distribution is graphically shown in figure 1. To characterize the structure of an uneven-aged forest means to describe mathematically the form of the distribution of trees as a function of diameter at breast height. It has been found (*10*, *11*) that this distribution can adequately be expressed by the distribution function.

$$df = k \cdot e^{-aX} . dX,$$

where k and a are constants, X stands for diameter at breast height, and e for the base of the natural logarithms. Upon taking logarithms it is seen that the logarithm of the number of trees is a linear function of diameter. By plotting the stand table of a forest on semilogarithmic paper in terms of diameter, we therefore obtain a straight line. It may also be stated that the number of trees in successive diameter classes form a geometric progression the ratio of which is found to be e^{ah}, where h is equal to the width of a diameter class. The French forester de Liocourt, who was working with uneven-aged selection forests, was the first to recognize this important fact. For numerical work, it is more convenient to describe a given distribution in terms of the exponential function given above.

The coefficients a and k have been determined for every stand listed in table 2. A graphical representation of each distribution was made on semilogarithmic paper in order to judge whether each of the calipered areas showed a distribution sufficiently balanced to be used in this study. No areas calipered were rejected, although it might have happened that too small areas had been taken as units, which would have resulted in too erratic a distribution to be used in this kind of work.

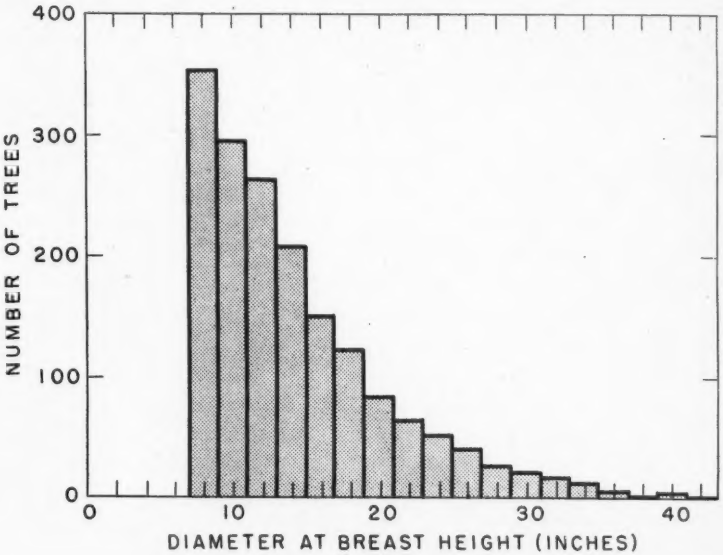

FIGURE 1.—Distribution of trees in stand No. 23, Tionesta scenic area, 21.4 acres.

Before the coefficients a and k can be calculated it is necessary to determine for each stand the upper diameter limit b of the distribution. Regarding the determination of this upper limit it must first be stated that the number of trees in the last highest diameter classes drops off rather abruptly and the points representing the number of trees in these highest diameter classes fall below the straight line that indicates the principal course of the distribution. In order to be able to define an upper limit of the distribution given in terms of the exponential function, the trees of the last few diameter classes are combined in a lower class in such a way that the plotted logarithms of the number of trees in that last class fall within the general trend of the distribution (fig. 2). The upper boundary of this new last class is taken as the upper limit of the distribution. In combining the trees of the last few classes, the actual basal area of these trees is first calculated; it is then determined how many trees of a diameter corresponding to the midpoint of the last class are required to make up the

same total basal area, and this number is taken as the frequency of the last class.

Having determined the upper limit b of the distribution, the characteristic coefficients a and k are determined for each stand by the method of least squares. The stand tables are used in their original

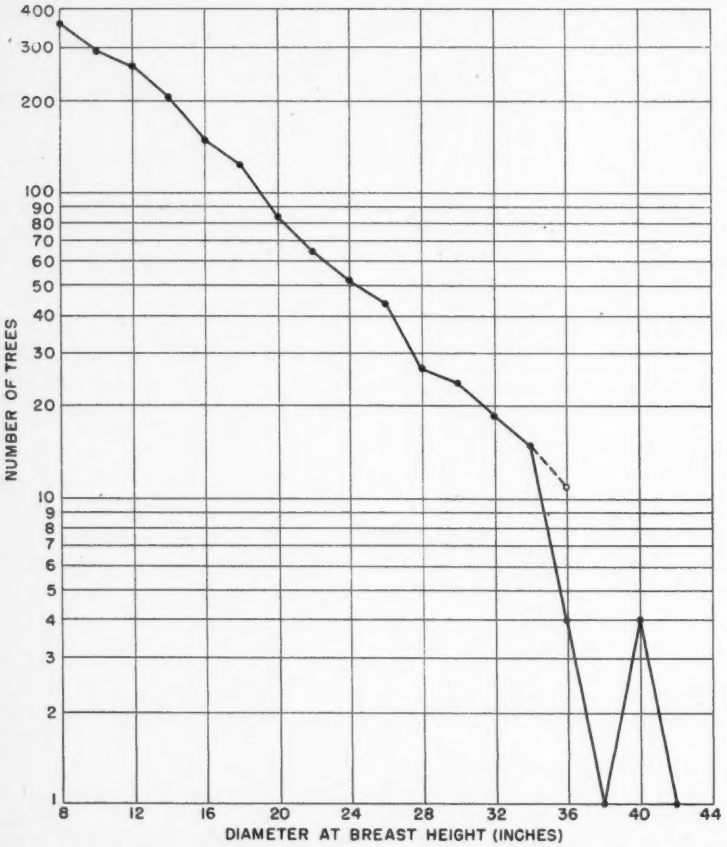

FIGURE 2.—Number of trees represented on semilogarithmic paper, stand No. 23, Tionesta scenic area, 21.4 acres.

form, without first calculating the number of trees per acre. Writing the equation

$$Y=K.e^{-aX}$$

in logarithmic form,

$$\log Y=\log K-a.X.\log e$$

a straight line is fitted to the logarithms of the frequencies Y. The weights of log Y are taken as equal. Details of the numerical com-

putation of a and k are shown in table 4. In the given example the coefficient K refers to an area of 21.4 acres. If the number of trees had first been divided by 21.4 acres it is easy to see that K would be 1/21.4 of the original K. We therefore divide K by the acreage, obtaining a new coefficient which shall be designated by k'. This coefficient refers to an area of 1 acre, in the sense that $k'.e^{-aX}$ gives directly the calculated number of trees in a given 2-inch diameter class. However since we wish to write the frequency distribution in the customary form $df=k.e^{-aX}dX$, so that

$$\int^{X_2} k.e^{-aX}.dX$$

represents the number of trees in a given diameter class with lower and upper limits X_1 and X_2, it is necessary to determine a new and final value k from k', such that

$$k'.e^{-aX_0}=\int_{X_1}^{X_2} k.e^{-aX}.dX$$

In this expression $X_0=\frac{1}{2}(X_1+X_2)$; the formula for computing k is easily found to be as follows, if the width of the diameter classes is equal to 2 inches:

$$k=\frac{a.k'}{e^{a}-e^{-a}}$$

or, approximately,

$$k=k'/2$$

TABLE 4.—*Computation of coefficients a, k, and b which characterize structure of virgin stand; stand No. 23, Tionesta scenic area, 21.4 acres*

Diameter at breast height (X)	Number of trees (Y)	log Y	X^2	X log Y
8	355	2.550	64	20.400
10	295	2.470	100	24.700
12	262	2.418	144	29.016
14	209	2.320	196	32.480
16	150	2.176	256	34.816
18	124	2.093	324	37.674
20	85	1.929	400	38.580
22	65	1.813	484	39.886
24	52	1.716	576	41.184
26	44	1.643	676	42.718
28	27	1.431	784	40.068
30	24	1.380	980	41.400
32	19	1.279	1,024	40.925
34	15	1.176	1,156	39.984
36	[1] 11	1.041	1,296	37.476
Total	1,737	27.435	8,380	541.310

[1] In the original stand table there were 4, 1, 4, 1 trees in the diameter classes 36, 38, 40, 42 respectively. The total basal area of these trees is equal to 80.70 square feet. The basal area of a 36-inch tree being equal to 7.07 square feet, we find an equivalent of 80.70/7.07=11 trees for the 36-inch class.

Normal equations: $N \log K - a \log e \Sigma X = \Sigma \log Y$ ($N=15$)
$\log K \Sigma X - a \log e \Sigma X^2 = \Sigma X \log Y$

The solution of the normal equation gives $a=0.1280$ $K=1127.1$
therefore $k'=1127.1/21.4=52.67$ and by formulae $k=a\ k'/(e^{a}-e^{-a}) \sim k'/2=26.3$

Upper limit of distribution $b=37$ inches.

ANALYSIS OF VARIATION IN STRUCTURE

When the numerical characteristics of the various virgin stands are compared, it is evident at once that there exists a close relationship between the coefficients, a and k. For a given value of a, which determines the rate at which the number of trees diminishes in successive diameter classes, higher and lower values of k indicate a higher or lower relative density between these stands. It is clear, therefore, that when values of a are low, which results, in a relatively large amount of heavy timber, the relative density in number of trees per acre must be small. The high correlation between these two coefficients is apparent from figure 3. The coefficient of correlation is

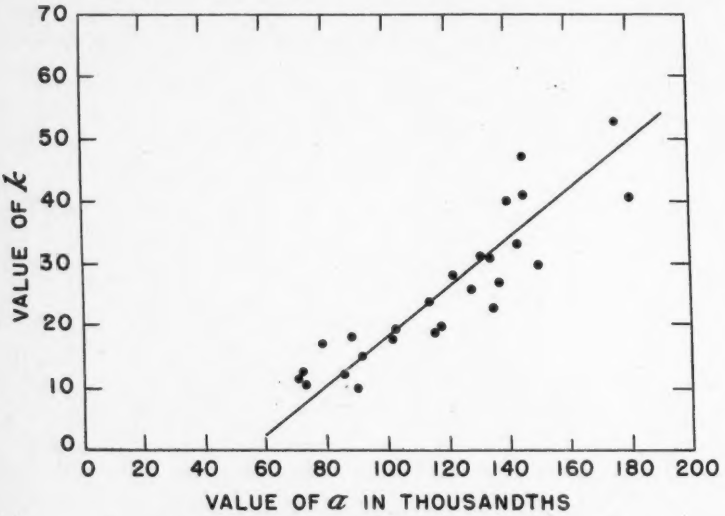

FIGURE 3.—Relation between the characteristics a and k.

equal to 0.9147. Large values of a are associated with large values of k. This is of special importance for the further evaluation of the data, since it enables us to calculate gradually differing diameter distributions within the range of the possible balanced structures of virgin forests of the beech-birch-maple-hemlock type. Similar correlations between the two coefficients a and k have previously been found for virgin forests in the higher altitudes of Mexico and for managed selection forests of Switzerland (*10*, *11*). It is possible, then, to calculate gradually differing balanced structures of virgin forests by determining the number of trees by diameter classes for distributions characterized by corresponding values of a and k. From the resulting stand tables it is easy to determine the distribution of basal area, cubic foot volume, or board foot volume. At the same time it is also possible to determine for each pair of the values a and k the corresponding value of b, the upper limit of the distribution. The corresponding value which indicates the proportion of hemlock for the resulting types of distribution may also be determined.

In determining corresponding values of these various characteristics, it is important to realize that no single characteristic may be regarded as a dependent variable. In order to reduce the coefficients to a comparable scale, it is necessary first to express them in deviations from their respective mean and in units of their standard deviations. Considering for the the moment only two coefficients, the values obtained may be plotted in a system of rectangular coordinates and a straight line fitted to the plotted points so that the sum of the squared perpendicular distances of these points from the line becomes a minimum. Working with three coefficients, a system of rectangular coordinates in three dimensional space would have to be used, and the line would have to be fitted to a cluster of points in space, again in such a manner that the sum of the squared residuals from the line would become a minimum. Through analogy, the idea may be carried over into four dimensional space if sets of four coefficients are to be compared, as in the present case. The technique of fitting lines in n-dimensional space is well developed and adequately described elsewhere (*1*, *2*, *7*). In the following outline of the various steps to be followed in the computational work only a few comments and explanations will be given. For presentation of the theory of the method the reader is referred especially to the paper of Kendall (*7*).

Designating the characteristics a, k, b, and the proportion of hemlock by X_1, X_2, X_3, and X_4 respectively, the correlation coefficients r_{12}, r_{13}, etc.[4] are first calculated. The numerical values of the correlation coefficients are as follows: $r_{12}=0.9147$; $r_{13}=0.0715$; $r_{14}=-0.5669$; $r_{23}=-0.1581$; $r_{24}=-0.6154$; $r_{34}=0.2694$. While some of the correlation coefficients are not significant, others are significant and highly significant. Since the structure of a stand is mainly determined by the two coefficients a and k, the high correlation existing between these two coefficients should be especially noted. The fact that the correlations between the coefficient b and the other characteristics is low is of minor importance because it merely indicates that the upper limit b of the diameter distribution varies only within narrow limits. The correlations between the proportion of hemlock and a, k, and b respectively are not high, indicating that for a given type of diameter distribution the proportion of hemlock may vary considerably.

The equation of the straight line to be fitted to the observed points lying in a four dimensional space is written in the following form:

$$\frac{x_1}{l_1}=\frac{x_2}{l_2}=\frac{x_3}{l_3}=\frac{x_4}{l_4}$$

where $x_1, x_2, x_3,$ and x_4 represent the four characteristics expressed in deviations from their mean and in units of their respective standard deviations; the symbols l_1, l_2, l_3, l_4 represent the direction cosines of the line. The line passes through the origin of coordinates. It can be shown that the line fitted by least squares as indicated above must actually pass through the point representing the weighted arithmetic averages of the various characteristics. This point may therefore rightfully be taken as the origin of coordinates. As soon as the direction cosines are known it is possible to calculate the coordinates

[4] Since the area w of the various stands was different, these coefficients were calculated by the formula $r_{xy}=\Sigma w(X-\overline{X})\ (Y-\overline{y})/\sqrt{\Sigma w(X-\overline{X})^2 \cdot \Sigma w(Y-\overline{y})^2}$.

for successive points lying on the line by assigning to either one of the four variables a series of values lying within the range of those actually observed. After expressing these values as deviations from the mean and in units of the standard deviation of the respective characteristic, a set of values of one selected variable, say x_1, is obtained. The corresponding values of x_2, for example, are obtained by multiplying the value of x_1 by the ratio $\frac{l_2}{l_1}$. The resulting values of x_2 must finally be transformed back into the original units. The corresponding values of x_3 and x_4 are found in a similar manner.

As shown by Kendall (*7*), the least square solution for the direction cosines leads to the following equations:

$$\begin{vmatrix} 1-\lambda & r_{12} & r_{13} & r_{14} \\ r_{12} & 1-\lambda & r_{23} & r_{24} \\ r_{13} & r_{23} & 1-\lambda & r_{34} \\ r_{14} & r_{24} & r_{34} & 1-\lambda \end{vmatrix} = 0 . \qquad (1)$$

$$\begin{aligned} l_1(1-\lambda)+l_2r_{12}+l_3r_{13}+l_4r_{14}&=0 \\ l_1r_{12}+l_2(1-\lambda)+l_3r_{23}+l_4r_{24}&=0 \\ l_1r_{13}+l_2r_{23}+l_3(1-\lambda)+l_4r_{34}&=0 \\ l_1r_{14}+l_2r_{24}+l_3r_{34}+l_4(1-\lambda)&=0 \end{aligned} \qquad (2)$$

The homogeneous equations (2) can be solved as soon as we know the multiplier λ which is obtained from the characteristic equation (1), representing an equation of the fourth degree in λ. Of the four possible solutions, the largest value of λ must be substituted in equations (2). It is obvious that the direct computation of λ becomes very laborious, if not impossible, as the order of the matrix increases. Through the application of an ingenious method of successive approximations, it is possible, however, to avoid altogether the separate evaluation of (1). The procedure explained by Hotelling (*1*, *2*) is as follows: Multiply the row of the matrix of the correlation coefficients by an initial set of trial values, these being equal to plus or minus 1. Since in the present example some of the correlation coefficients are negative, the trial values for the first, second, third, and fourth row are taken as 1, 1, −1, and −1, respectively. After multiplying successive coefficients in every row by successive trial values (by starting for each row with the first trial value)[5] and adding the results, divide the sums obtained for each row by the largest sum obtained. The resulting quotients are taken as the new trial values and the procedure is repeated by multiplying the new trial values with the original matrix until the quotients become stationary. The first two and the last two steps of the computation are shown below. In actual practice it

[5] In other words, the writers would multiply the matrix of the correlation coefficients with the one column matrix $\begin{pmatrix} 1 \\ 1 \\ -1 \\ -1 \end{pmatrix}$.

is, of course, not necessary to write down each individual product when using a calculation machine.

					First trial value
1	. 9147	. 0715	−. 5669		1
. 9147	1	−. 1581	−. 6154		1
. 0715	−. 1581	1	. 2694		−1
−. 5669	−. 6154	. 2694	1		−1
					Second trial value
1. 0000	. 9147	−. 0715	. 5669	2. 4101	. 8965
. 9147	1. 0000	. 1581	. 6154	2. 6882	1. 0000
. 0715	−. 1581	−1. 0000	−. 2694	−1. 3560	−. 5044
−. 5669	−. 6154	−. 2694	−1. 0000	−2. 4517	−. 9120
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
					Twelfth trial value
. 9607	. 9147	−. 0159	. 4814	2. 3409	. 9608
. 8788	1. 0000	. 0351	. 5226	2. 4365	1. 0000
. 0687	−. 1581	−. 2217	−. 2288	−. 5399	−. 2216
−. 5446	−. 6154	−. 0597	−. 8492	−2. 0689	−. 8491
					Stationary quotients
. 9608	. 9147	−. 0158	. 4814	2. 3411	. 9609
. 8788	1. 0000	. 0350	. 5225	2. 4363	1. 0000
. 0687	−. 1581	−. 2216	−. 2287	−. 5397	−. 2215
−. 5447	−. 6154	−. 0597	−. 8491	−2. 0689	−. 8492

In the present case 13 successive iterations were necessary before the quotients became stationary. The convergence can be substantially increased by squaring the matrix of the correlation coefficients and applying the process of successive approximations to the squared matrix. The stationary quotients finally obtained are not yet the desired direction cosines but represent numbers which are proportional to them. Since the sum of the squared direction cosines must be equal to 1, these are found by squaring the quotients 0.9609, 1.0000, −0.2215, −0.8492, taking the square root of the sum of these squares and dividing the result into the stationary quotients. In the present example we obtain

Stationary quotients		Direction cosines	
q	q^2	$=q/1.6412$	
0. 9609	0. 92332881	0. 5855	0. 3424
1. 0000	1. 00000000	0. 6093	0. 3712
−0. 2215	0. 04906225	−0. 1350	0. 0182
−0. 8492	0. 72114064	−0. 5174	0. 2677
	2. 69353170		
	$\sqrt{2.69353170}=1.6412$		0. 9999

As a check, the squares of the calculated direction cosines have been added in the last column of the above computations.

STRUCTURAL TYPES

Since the equation of the straight line fitted to the cluster of points representing corresponding values of the various characteristics of the virgin stands is known, for successive values of one of the characteristics the corresponding values of the other three characteristics can now be calculated. It makes no difference to which one of the four characteristics such arbitrary and gradually differing values are assigned. Geometrically speaking, the coordinates of a series of points lying on the straight line fitted to these points are being determined. Accordingly, some successive values of the characteristic a are assigned by taking x_1 equal to -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, and 2.0. The corresponding values of

$$x_2=\frac{l_2}{l_1}x_1,\ x_3=\frac{l_3}{l_1}x_1,\ x_4=\frac{l_4}{l_1}x_1$$

are given in table 5. In the same table are listed the weighted means of the four characteristics, the standard deviation of each characteristic for an observation of weight one (the weight being equal to the area of a stand), and the standard deviation for an average area of 419.2/26=16 acres. When expressing the values of x_1, x_2, x_3, and x_4 in the original units of the coefficients, it must be kept in mind that the average area of a stand was equal to 16 acres. The values of x_1, x_2, x_3, and x_4 should therefore be multiplied by $s/\sqrt{16}$ and added to the weighted means of the respective coefficients in order to obtain values lying within the range of those actually observed. The various coefficients of a corresponding to the assigned values of x_1 are obtained as shown in table 6. By using the mean and the standard deviation of the other coefficients, the corresponding values of all four characteristics which have been used to describe the structure of the virgin forests are obtained in the same way. These values are listed in table 7. It will be noticed that the coefficient k corresponding to $x_1=-2.0$ turned out to be negative. Since it is obviously impossible for k to be negative, and a deviation from the mean as large as this cannot occur in practice, this coefficient must be discarded. This is easily understood by looking at figure 3, where it is seen that for $a=0.00536$ the line falls below the axis of the abcissa. The remaining seven sets of coefficients characterize seven gradually differing structural types of virgin forests of the beech-birch-maple-hemlock type.

TABLE 5.—*Weighted means of characteristics and standard deviations for observations of weight one, together with corresponding values of* x_1, x_2, x_3, x_4

Characteristic	a (x_1)	k (x_2)	b (x_3)	Proportion of hemlock (x_4)
Weighted mean	0.1134	23.5	34.6	33.2
Standard deviation of observation of weight 1	.1197	45.9	14.0	54.7
Standard deviation of observation of weight 16	.0299	11.5	3.5	13.7
Corresponding values of x_1, x_2, x_3, and x_4	2.0	2.081	−.461	−1.767
	1.5	1.561	−.346	−1.326
	1.0	1.041	−.231	−.884
	.5	.520	−.115	−.442
	0	0	0	0
	−.5	−.520	.115	.442
	−1.0	−1.041	.231	.884
	−1.5	−1.561	.346	1.326
	−2.0	−2.081	.461	1.767

TABLE 6.—*Method of obtaining the various coefficients of "a" corresponding to the assigned values of "x_1"*

x_1	$x_1 \cdot 0.1197/\sqrt{16} = 0.0299 \cdot x_1$	$a = 0.1134 + 0.0299 \cdot x_1$
2.0	0.0598	0.1732
1.5	.0448	.1582
1.0	.0299	.1433
.5	.0150	.1284
0	0	.1134
−.5	−.0150	.0984
−1.0	−.0299	.0835
−1.5	−.0448	.0686
−2.0	−.0598	.0536

It is an easy matter to calculate the number of trees per acre and by diameter classes for each structural type. For the diameter class ranging from 7 to 9 inches, the following value is obtained for type A:

$$\int_7^9 47.4e^{-0.1732x} \cdot dx = \frac{47.4}{-0.1732}\left(e^{-0.1732 \cdot 9} - e^{-0.1732 \cdot 7}\right)$$
$$= -273.67(0.2104 - 0.2975) = 23.8$$

TABLE 7.—*Characteristics for gradually differing structural types of virgin forests*

Structural type	a	k	b	Proportion of hemlock
			Inches	*Percent*
A	0.1732	47.4	34.0	9.0
B	.1582	41.5	34.4	15.0
C	.1433	35.5	34.8	21.1
D	.1284	29.5	35.2	27.1
E	.1134	23.5	35.6	33.2
F	.0984	17.5	36.0	39.3
G	.0835	11.5	36.4	45.3
H	.0686	5.5	36.8	51.4

In table 8 are listed the number of trees per acre and by diameter classes for eight structural types. The total number of trees per acre decreases gradually from type A up to type H, while the proportion of heavy timber becomes successively larger. From table 9 it is seen that a large proportion of heavy timber occurs together with a high percentage of hemlock. This observation is of considerable importance for a clear understanding of the development of these virgin forests. There are two possible ways of interpreting this fact. There may be localities and site conditions on which there is permanently a high proportion of hemlock, while on other sites hemlock is only sparsely represented. The various structural types may also represent various stages in the development of the virgin forest. It is this latter interpretation with which this study is mainly concerned. Field studies have deomonstrated that a gradual change in the composition of the virgin stands takes place. A heavy stand of hemlock with hardwoods in the understory will ultimately break up and be replaced by a stand with only a small percentage of hemlock. In stand 19 of the Tionesta tract, for example, the ground was covered with many decayed hemlock stems all lying in the same direction as a result of a serious windstorm. Part of the existing

stand is composed of nearly pure hardwoods. In the shade of hardwoods hemlock reproduction is gradually establishing itself and in decades to come hemlock will probably again become the dominant species in the higher diameter classes. As established from the age of mature hemlock, a period of 200 to 300 years must elapse before a complete cycle in the evolution of a virgin stand is completed. When considering a period of several decades only, however, the structure of a stand as characterized by one of the types A to H remains essentially the same. It may therefore, be said to be balanced, despite the fact that over a period of 200 and more years the composition of the stand undergoes a gradual change. With the exception of the extreme types G and H it is likely that any of the other structural types could be maintained indefinitely if the forest were managed on a selection basis.

TABLE 8.—*Stand tables for gradually differing structural types of virgin forests*

Diameter at breast height (inches)	Trees per acre in stand type—							
	A	B	C	D	E	F	G	H
	Number	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
8	23.8	23.5	22.6	21.2	19.0	16.0	11.8	6.4
10	16.9	17.1	17.0	16.4	15.2	13.1	10.0	5.5
12	11.9	12.5	12.8	12.7	12.1	10.8	8.5	4.8
14	8.4	9.1	9.6	9.8	9.6	8.8	7.3	4.2
16	6.0	6.6	7.2	7.6	7.7	7.3	5.9	3.7
18	4.2	4.8	5.4	5.9	6.1	6.0	5.1	3.2
20	3.0	3.5	4.1	4.5	4.9	4.9	4.3	2.8
22	2.1	2.6	3.0	3.5	3.9	4.0	3.7	2.4
24	1.5	1.9	2.3	2.7	3.1	3.3	3.1	2.1
26	1.1	1.4	1.7	2.1	2.5	2.7	2.6	1.9
28	.7	1.0	1.3	1.6	2.0	2.2	2.2	1.6
30	.5	.7	1.0	1.3	1.6	1.8	1.9	1.4
32	.4	.5	.7	1.0	1.2	1.5	1.6	1.2
34	.1	.3	.5	.8	1.0	1.3	1.4	1.1
36				.1	.3	.5	.8	.8
Total	80.6	85.5	89.2	91.2	90.2	84.2	70.2	43.1

TABLE 9.—*Total volume and percentage distribution of volume by diameter groups*

Structural type	Total volume per acre	Distribution of volume by diameter groups			
		Small timber, 7 to 13 inches	Medium timber, 17 to 21 inches	Large timber, 21 inches and over	Proportion of hemlock
	Cubic feet	*Percent*	*Percent*	*Percent*	*Percent*
A	2,810	28	39	33	9.0
B	3,290	24	37	39	15.0
C	3,780	21	36	43	21.1
D	4,330	18	34	48	27.1
E	4,780	15	31	54	33.2
F	5,000	12	29	59	39.3
G	4,740	10	26	64	45.3
H	3,300	8	23	69	51.4

The significance of the various structural types is still better understood when computing the basal area and volume per acre and their distribution over three main diameter groups. In practice it is customary to characterize the structure of a stand by giving the total

volume per acre and the percentage of small timber, medium timber, and large timber. The limits of these three main diameter groups are often taken as 7 to 13 inches, 13 to 21 inches, and 21 inches and over. The percentages in basal area and volume are very much the same so that it is sufficient to comment on the results expressed in terms of cubic foot volume, as given in table 9. The corresponding data for basal area are given in table 10. It is interesting to note that the volume per acre increases gradually from type A up to type F, where it reaches a maximum of 5,000 cubic feet per acre. At this point, however, the volume drops rather rapidly to 4,740 and 3,300 cubic feet per acre. Although both of these last types still show a gradual decrease in number of trees by diameter classes, the sudden drop in volume is a clear indication that stands of this structure approach a stage where there is too much heavy timber to allow the presence of a sufficient amount of volume in the smaller diameter classes. The next stage in the development of such a stand is characterized by increased mortality of the overmature hemlock and a subsequent increase of volume in the smaller diameter classes. Since these younger trees will consist mostly of hardwoods the further development will lead to a structure similar to type A.

TABLE 10.—*Total basal area and percentage distribution of basal area by diameter groups*

Structural type	Basal area per acre	Distribution of basal area by diameter groups		
		Small timber, 7 to 13 inches	Medium timber, 17 to 21 inches	Large timber, 21 inches and over
	Square feet	*Percent*	*Percent*	*Percent*
A	80.8	33	39	28
B	92.8	29	38	33
C	105.0	26	37	37
D	117.7	22	35	43
E	127.7	19	33	48
F	131.3	16	31	53
G	121.9	13	28	59
H	83.4	11	26	63

The total volume per acre and its distribution by diameter groups as calculated for the various structural types is a valuable guide in appraising the normal volume of a forest of the beech-birch-maple-hemlock type under sustained-yield management. It is quite evident that a forest manager would not attempt to maintain the largest possible growing stock capable of producing a sustained yield but rather a growing stock similar to that of type A, B, or C. Through periodic cuttings and thinnings it would be possible to modify such a structure, especially as far as composition by species is concerned. The normal growing stock in an uneven-aged forest is not a fixed quantity but a variable which may fluctuate rather widely to suit changing silvicultural and economic conditions. The established structural types represent the best available basis by which to judge the limits within which the balanced volume of an uneven-aged forest may fluctuate without endangering sustained production.

GROWTH

By using increment borings at breast height and ring counts on the stump the average diameter increment for the last 10 years was determined in a number of stands and localities. It would have been too laborious a task to determine the growth separately for every area calipered. The data collected refer to an entire tract. They can therefore not be correlated with the structural type which has been characterized by the various coefficients previously discussed. These coefficients refer to subdivisions of the tracts. It is doubtful, however, if any significant correlations between structure and growth could be established because the growth of an area depends to a considerable extent not only on the structure and composition of the stand but also on site quality. Since on one and the same site the structure may vary considerably (because of the long-term cycle of evolution of the forest) it is likely that differences in growth due to site are overshadowed by differences in structure, and vice versa.

The average diameter increment at breast height, calculated separately for hemlock and hardwoods for a number of tracts, is shown in figure 4. The data obtained from the various areas show relatively small differences. On the whole, no pronounced trend of diameter increment is discernible, the average increment being about the same throughout the diameter classes. The growth of the hardwoods, however, is generally greater than the growth of hemlock. This becomes more evident after balancing the original growth data by fitting a straight line or a parabola to the data shown in figure 4. By using the balanced diameter increment thus obtained, the percentage volume increment by diameter classes, as well as total volume increment and volume increment per acre, are easily calculated. From the 8-inch diameter class up to the 30-inch diameter class the percentage volume increment diminishes from about 2.5 percent to 0.9 percent for hemlock and from about 3.0 percent to 0.7 percent for hardwoods. In the smaller diameter classes the relative growth of hemlock is therefore smaller than that of the hardwoods, while the reverse is true for the higher diameter classes.

Additional data on volume increment in percent of volume, and volume increment per acre, are given in table 11. For the total volume of the trees 7 inches in diameter and over, the percentage volume increment of hemlock is consistently lower than that of the hardwoods. The total volume increment per acre ranges between 44 and 67 cubic feet, the average of all tracts combined (weighted according to area calipered) being equal to 50.7 cubic feet. This increment represents gross increment which, over a period of years, will be largely offset by the annual mortality. It is quite evident that the same forest would yield a decidedly larger increment per acre with systematic management under a group selection or group shelterwood system, while at the same time the normal growing stock per acre would probably be somewhat smaller than the actual growing stock in the virgin stands. However, even with the same amount of total volume per acre, the distribution of the volume by diameter classes would be different, more volume being in the lower diameter classes and less in the upper diameter classes.

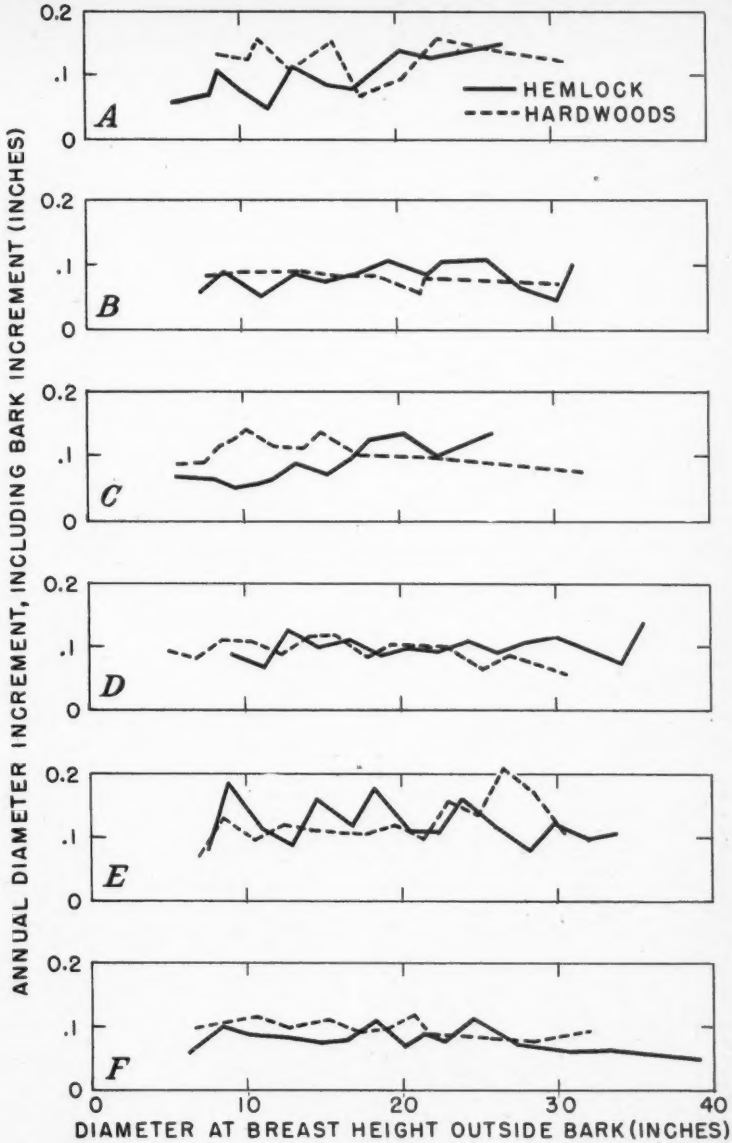

FIGURE 4.—Annual diameter increment, including bark increment, in terms of diameter at breast height outside the bark for trees on various tracts: *A*, Hess; *B*, Ricketts; *C*, Rightmeier; *D*, Larson; *E*, Dunham; *D*, Tionesta.

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SUMMARY

By the use of the distribution function $df=k\cdot e^{-aX}\cdot dX$ the diameter distributions of various virgin stands of the beech-birch-maple-hemlock type have been compared statistically. A high correlation between the two coefficients a and k was found to exist. Large values of a are associated with large values of k. This important relationship enabled the calculation of gradually differing diameter distributions within the range of the possible balanced structures of virgin forests. For a given value of a, which determines the rate at which the number of trees diminishes in successive diameter classes, higher and lower values of k indicate a higher and lower density between these stands. In addition to the coefficients a and k, the stands were further characterized numerically by the upper diameter limit b, and the proportion of hemlock. These characteristics proved in turn to be correlated between themselves as well as with a and k.

By applying statistical methods, seven sets of four coefficients (a, k, b, and proportion of hemlock) were obtained to characterize seven gradually differing structural types of these virgin forests. The total number of trees per acre was found first to increase and then to decrease gradually from type A up to type H, while at the same time the proportion of heavy timber became successively larger. A large proportion of heavy timber occurred together with a high percentage of hemlock. This conforms with the view that the various structural types represent to a large extent different stages in the long time development of the virgin forests. A heavy stand of hemlock with hardwoods in the understory will ultimately break up and be replaced by a stand of hardwoods with only a small percentage of hemlock. However, because of the relatively low correlation between the proportion of hemlock and the characteristics a, k, and b, the proportion of hemlock may deviate considerably from the average values given for the different structural types.

TABLE 11.—*Volume increment per acre and volume increment in percent of volume for hemlock and hardwoods*

Tract	Volume increment per acre			Percentage volume increment		
	Hemlock	Hardwoods	Total	Hemlock	Hardwoods	Total
	Cubic feet	*Cubic feet*	*Cubic feet*	*Percent*	*Percent*	*Percent*
Hess	5.3	61.4	66.7	1.4	1.6	1.6
Ricketts	15.1	28.8	43.9	1.0	1.3	1.1
Rightmeier	14.2	42.4	56.6	1.3	1.6	1.5
Larson	32.9	23.1	56.0	1.1	1.4	1.2
Dunham	31.5	22.4	53.9	1.3	1.7	1.5
Tionesta	18.6	27.3	45.9	.7	1.5	1.0

It was found that the volume per acre increases from type A up to type F, where it reaches a maximum of 5,000 cubic feet per acre. The volume then drops to 4,740 and 3,300 cubic feet per acre, a further indication that these types apparently represent a somewhat over-aged condition of the virgin forest. Stands of this structure have relatively too much heavy timber to allow for sufficient volume in the lower

diameter classes. The next stage in the development will be characterized by an increased mortality in the larger diameters and a subsequent increase of volume in the smaller diameter classes. The tables 9 and 10, which show the percentage distribution of volume and basal area by three main diameter groups, explain this situation more clearly.

The structural types represent a basis by which to judge the limits within which the balanced volume of an uneven-aged forest of the birch-beech-maple-hemlock type may fluctuate while the structure of the forest remains sufficiently balanced to insure sustained production. It may be pointed out, however, that the normal structure of a managed forest of the type here considered may be somewhat different from that of the virgin forest, having probably a relatively higher volume in the lower diameter classes.

Analysis of growth showed that the percentage volume increment diminishes with increasing diameter from about 2.5 percent to 0.9 percent for hemlock and from about 3.0 percent to 0.7 percent for hardwoods. The gross volume increment per acre ranges between 43.9 and 66.7 cubic feet, the average of all stands calipered being equal to 50.7 cubic feet. This gross increment is, in part, offset by the current average mortality. As a stand gradually changes from one structural type with a low volume per acre to another with a relatively high volume per acre, the gross increment will exceed the current mortality. In the later stages of this development, when the volume again decreases, the current mortality will be greater than the current gross increment.

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WEARING TESTS ON FABRIC BLENDS OF NEW AND RECLAIMED WOOL FIBER[1]

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INTRODUCTION

Since the curtailment of the use of new wool for civilian needs was effected by the Office of Production Management (January 1942) and later by the War Production Board, the question of the relative serviceability of fabrics containing various blends of new and reclaimed wool is becoming increasingly important. In addition, legislation[3] has given the ultimate consumer access to information, in the form of labels, as to the percentage and type of wool in a specific article; however, such information is of little practical value unless a reasonably correct interpretation of the factual material is possible. In 1940, service of performance tests of garments made of dyed flannel fabrics of various blends of new and reclaimed wool fiber were begun at the South Dakota Agricultural Experiment Station. Certain chemical and physical properties of the fiber and fabric before dyeing had been determined at an earlier date and subsequently reported by Bailey (*4*).[4]

Certain questions arise: Is it possible to predict the wearing qualities of a fabric from laboratory tests or do individual differences in wear habits tend to mask differences in fabric? What chemical changes in the fiber of wool accompany storage and wear of fabrics? How do garments wear out? It is not to be expected that these questions will be answered by this study alone, but need for further investigation of possible trends should be indicated.

As a review of the literature shows, actual service tests are coming to the fore, not to take the place of, but to supplement, and if possible to prove the reliability of predication of service by laboratory tests (*7, 8, 13, 15*). Sommaripa (*15*) has concluded that serviceability tests are sensitive enough to show differences in performance of given fabrics. Although extensive studies have been made of wool fiber and subsequent fabric characteristics (*4, 10, 11, 12*), very little has been published on actual wearing tests of wool fabrics of known fiber history. The Bureau of Animal Industry of the United States Department of Agriculture in cooperation with the Bureau of Home Economics, in 1937, reported a study of serviceability tests on blankets made from four blends of wool (*7*). There are in progress at Government laboratories studies (*5*) involving a comparison of the serviceability of blankets prepared from blends of three-eighth blood new wool with varying amounts of good- and poor-quality reworked wool,

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[3] The Wool Products Labeling Act, effective July 15, 1941.

[4] Italic numbers in parentheses refer to Literature Cited, p. 500.

a comparison of the serviceability of blankets containing various percentages of reworked wool and mohair with new wool, and the serviceability of suitings made from new wool and blends of new wool with reworked wool and spun rayon. All reports emphasize the need of knowing the fiber history and details of fabric manufacture.

MATERIALS

The flannel fabrics used in this investigation were woven at the Lowell Textile Institute [5] and have a 2 by 2 even twill construction. Uniform blends were used for both warp and filling yarns. Further details of fiber properties and manufacture of these fabrics have been reported by Bailey (*3*). In brief, new wool from Rambouillet sheep raised at the South Dakota State College and high-quality pastel sweater clippings purchased on the market by the Lowell Textile Institute were blended in various proportions. Fabric No. 100 contains 100 percent new wool, fabric No. 75 is made of approximately 75 percent new wool and 25 percent clippings, fabric No. 50 is made of approximately 50 percent new wool and 50 percent clippings, fabric No. 25 is made of approximately 25 percent new wool and 75 percent clippings.

According to labeling definitions of the Wool Products Labeling Act, "reprocessed wool" is the fiber that results "when wool has been woven or felted into a wool product which without ever having been utilized in any way by the utlimate consumer, subsequently has been made into a fibrous state." The sweater clippings may not be classified as "reprocessed wool" but simply as "wool," since under "wool" are included "yarns and other wastes broken off by or entangled in the combing, drawing and spinning processes, and unused knit wool products made of new wool, such as sweater clippings. These partially processed wastes are included under the term 'wool' on the basis that the damage and deterioration which they undergo in being reduced to a fibrous state for reuse, is not sufficient to seriously diminish their original, natural intrinsic protective and service qualities" (*1, p. 19*). It may be concluded that differences found between blends of new wool and the reclaimed sweater clips used in this study would tend to be exaggerated if "reprocessed" wool as defined by the Wool Products Labeling Act and of the same original quality as the clips were used. The term "reclaimed wool" (not used in labeling rules) will be used to indicate the sweater clippings in this study since it is misleading to call it simply "wool."

Following the fiber and fabric studies previously mentioned, portions of the four fabrics were dyed navy blue by a commercial dyer who used identical dyestuffs and processes for each fabric. The description given of the dyeing process [6] is as follows: Wetting out of the material was executed in weak ammonia water for 15 minutes at 110°–120° F. and then in two fresh water rinses at the same temperature. The material to be dyed was then immersed in a water bath (140° F.) to which was added 10 percent Glauber salt and 3 percent acid alizarin blue. The temperature of the water was brought to 195° F. in ½ hour and held there for an additional 1¼ hours. The dyed material was rinsed until the water was clear.

[5] Lowell Textile Institute, Lowell, Mass.
[6] Dyer's specifications.

Fabric yardage losses incurred in dyeing range from approximately 3.1 to 5.8 percent. The largest percentage loss was found in fabrics No. 100 and No. 50; the smallest in fabric No. 75. Accompanying these losses in fabric yardage there appeared a significant (1 percent level) decrease in warpwise breaking strength (strip test) for all fabrics. Fillingwise breaking-strength values were inconsistent in their variation. Only fabric No. 75 showed a decrease in bursting-strength value. The usual evidences of shrinking were present in that thickness and number of yarns per inch increased for both fabrics.

METHODS

WEARING TESTS

Twelve four-gore skirts were made from the four navy blue wool flannel fabrics and issued to women students at South Dakota State College who agreed to cooperate in the wearing tests. A relatively simple-to-make, conservative, and well-fitting skirt design was chosen to facilitate subsequent fabric sampling and to avoid as far as possible, localized wear due to construction or design details. The selection of college girls made rather close supervision of the wearing periods possible, yet allowed full play of individual wearing habits under ordinary wearing conditions. It was decided that all the garments should be withdrawn from service for testing at the end of the time interval in which one garment showed definite evidences of wear. Accordingly, each skirt was worn a total of 1,000 hours, which approximates the length of time equivalent to the wear a college girl would ordinarily give a skirt during a school year. Careful records of hours worn, type of activity, brushing, pressing, evidences of wear, and damage to garment were kept by each individual wearing one of the skirts. After each 150-hour period the skirts were inspected. Measurements were taken both before and after dry cleaning to indicate stretching or shrinking. Then shirts were dry-cleaned commercially, always at the same establishment where standard procedures were assured.

In the dry-cleaning treatment [7] a solvent (Stoddard solvent, U. S. Department of Commerce commercial standard CS3–40), was circulated through garments placed in a cylindrical washer. A filter aid was added to the solvent after which the solvent was drawn continuously through a filtering device until clear. A stock solution consisting of 2 parts soap, 1 part water, and 1 part solvent was run on the batch for approximately 20 to 30 minutes. Nearing the end of the soap run, more filter aid was added and the solution was again drawn through a filter until clear. The garments were dried and deodorized in a tumbler and pressed with an ordinary steam press.

PHYSICAL MEASUREMENTS OF FABRIC AND GARMENTS

Breaking strength (strip test) and elongation, bursting strength and elongation, fabric thickness, number of yarns per inch, yarn number, and yarn twist measurements were made on the fabrics as received from the dyers and on control fabrics which were stored for a time equivalent to the skirt-wearing period. All physical measurements of yarn and fabric were made in a laboratory maintaining a

[7] Dry-cleaning specifications.

temperature of 70° F.±2° and a relative humidity of 65±2 percent. Standard procedures of the American Society for Testing Materials (*2*) were used throughout, unless otherwise noted. The testing equipment included a motor-driven Scott tester for breaking-strength and elongation determinations; a ball-burst attachment for the Scott tester, using 1-inch steel balls for burst-strength and elongation determinations; a Schiefer compressometer, the presser foot being 0.375 inch in diameter and the pressure equal to 3.4 pounds per square inch, for thickness measurements; a micrometer yarn counter for number of yarns per inch; a Suter yarn numbering balance (results used in the adjustment of tension for yarn-twist measurement); and a hand-turned new-type Suter precision twist tester for the determination of twists per inch.

Similar measurements, with the exception of yarn twist and yarn number, were made on material from the 12 skirts. It was necessary to curtail the number of physical tests used to measure the relative wearing qualities of the 4 fabrics because of visible evidence of localization of wear.

In order to determine fabric strength in various parts of the skirt, each skirt was divided into three sections, designated as top, middle, and bottom. The top section included the skirt area extending from the waistline to the approximate top of the thighs, or to the bend of the skirt if one were in a sitting position. The middle section extended down approximately two-thirds the length of the skirt, and the bottom section included the lower part of the skirt. Care was taken to approximate the same relative sampling location regardless of the size of the skirt. Five breaking-strength samples, 1½ by 6 or 7 inches, warpwise and fillingwise, were cut from both the front and back of the skirt for each of the three sections. For calculation, it was assumed that the wear on the back left gore, top section, was similar to that on the back right gore, top section. It was suggested that wet breaking-strength measurements might show greater differences than dry breaking-strength measurements; however it was impossible to include both. In addition, it is well known that wool loses strength when wet and under normal conditions wool garments are worn in a more or less dry state.

Ten bursting-strength samples, 4 by 4 inches, were cut from each skirt, the sampling being scattered to represent, as far as possible, all parts of the skirt and to avoid inclusion of indentical warp and filling yarns and identical placement with reference to skirt seams. By such a method the composite bursting strength of the worn fabric should be indicated, or if inadequate sampling were suggested by statistics, real bursting-strength variation in different parts of the skirts would be intimated.

Fabric-thickness and yarn-count (number of yarns per inch) determinations were made on each of the bursting-strength samples.

CHEMICAL ANALYSES

Moisture, sulfur, nitrogen, and ash content of the four blends were determined after (1) fabrics were received from the dyers, (2) after storage, and (3) after the total wear period. Samples of the wool fiber used in the analyses were obtained in a random manner for all blends. A drying oven maintained at 105° C. was used to bring 0.5- to 1.0-gm.

samples for moisture determinations to constant weight. These samples were transferred to a Parr bomb for total sulfur measurement. Total nigrogen present was determined by the Kjeldahl method. Samples were ignited and ashed to constant weight, from which the percent of ash was determined. All percentage calculations of sulfur, nitrogen, and ash were based on moisture-free weights.

PRESENTATION AND INTERPRETATION OF DATA

COMPARISON OF BLENDS

By appearance alone it would be difficult, if not impossible, to distinguish between the four blends, but physical tests leave little doubt as to their dissimilarity. Throughout these blend comparisons it is interesting to keep in mind that it was reported (*3*) that the average length of the new fiber was 40 percent greater than that of the reclaimed wool and the average number of crimps per inch was more than 10 percent greater in the new wool. No difference in average contour ratio was found in the wool. The physical-test data for the dyed flannel fabrics appear in table 1.

Mean strip breaking-strength values, which range from 32.4 pounds for blend No. 100 to 17.4 pounds for blend No. 25 warpwise, and 27.7 to 16.7 pounds, fillingwise, indicate real strength differences according to a *t* test among all four blends, increasing progressively from blend No. 100 to No. 25. Based on the breaking-strength values for the 100-percent new-wool fabric, there were successive losses in warp strength which amounted to 12, 28, and 46 percent and which resulted from the increased percentage of the reclaimed wool per fabric. In filling strength, the losses range from 18 to 32 to 40 percent, indicating a more decisive initial loss due to blending but a tendency to level off more rapidly than did warp strength.

Bursting-strength determinations also reveal a significant strength decrease from No. 100 to No. 25. Figure 1 graphically illustrates the percentage strength of the four blends as evidenced by breaking- and bursting-strength tests.

Fabric elongation, as shown by strip-elongation determinations, decreases somewhat with increasing percentage of reclaimed wool. Because of the greater number of shorter fibers in the fabrics containing the reclaimed wool, this was to be expected. Warpwise strip elongation gave evidence that fabrics No. 100 and No. 75 had a greater fabric elongation than No. 50 and No. 25. In the filling direction, fabric elongation decreased significantly from fabric No. 100 to No. 50. Comparison of warpwise elongation and fillingwise elongation for each blend shows a real difference only for blends No. 100 and No. 75. Bursting-strength elongation for all fabrics was the same, except for No. 25 which was somewhat less.

The number of yarns per inch for all fabrics decreased only slightly throughout the series, both warpwise and fillingwise. Fabric thickness was approximately the same with the exception of blend No. 25, which was significantly (1-percent level) thinner than the other fabrics. Yarn twist and yarn number (typp system) for the four fabrics was very similar, except that yarn twist for fabric No. 25 was somewhat greater than that of other blends.

TABLE 1.—*Physical-test data for dyed flannels, 1941*

Test	Unit of measure	No. 100				No. 75				No. 50				No. 25			
		Warp		Filling		Warp		Filling		Warp		Filling		Warp		Filling	
		Mean	Standard deviation	Mean	Standrad deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Strip breaking strength	Pounds	32.4	0.97	27.7	0.68	28.6	0.84	22.8	1.32	23.4	0.91	18.7	0.48	17.4	0.52	16.7	0.82
Bursting strength	Pounds	81.10	1.89			69.70	3.44			61.40	4.14			53.35	1.96		
Strip breaking-strength elongation.	Inches	.92	.06	1.06	.08	.84	.05	.96	.05	.72	.04	.75	.05	.66	.05	.69	.09
Bursting-strength elongation.	Inch	.38	.13			.38	.13			.38	.13			.28	.08		
Yarns per inch	Number	45.5		40.0		45.3		38.6		43.4		40.2		43.9		39.9	
Fabric thickness	Thousandths of an inch.	35.45	.98			34.95	.37			34.40	.91			32.25	.26		
Yarn twist (per inch)	Number	13.20	1.04	12.69	.51	12.82	.72	13.02	.92	12.48	.92	12.36	.58	12.57	.88	12.86	1.12
Yarn No	Typp	6.35		6.25		6.90		6.75		6.78		6.88		7.94		7.56	

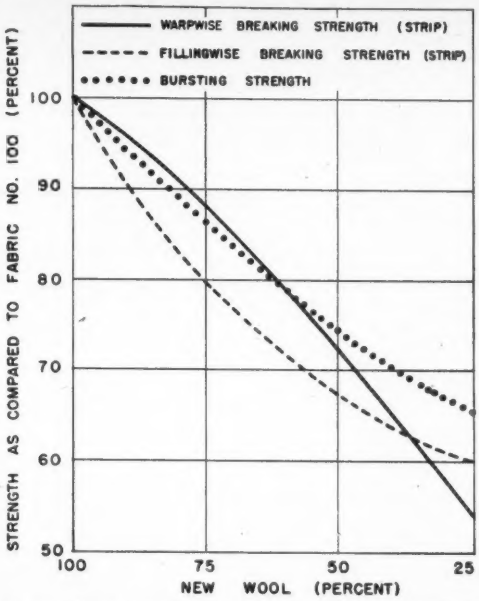

FIGURE 1.—Warpwise and fillingwise breaking-strength and bursting-strength values, according to percentage composition, of the four fabric blends after dyeing.

Chemical analyses of the four fabrics after dyeing reveal, in general, several trends as seen in table 2. The percentage of ash for fabrics

TABLE 2.—*Percent total ash, nitrogen, and sulfur calculated on a moisture-free basis for the 4 fabric blends after dyeing, storage, and wear*

Treatment and fabric No.	Ash	Nitrogen	Sulfur
Dyed:	*Percent*	*Percent*	*Percent*
100	0.77	16.64	3.71
75	.81	16.65	3.64
50	.87	16.50	3.65
25	.85	16.31	3.62
Stored:			
100	.87	16.00	3.55
75	.98	15.83	3.57
50	.76	15.87	3.52
25	.97	16.00	3.52
Worn:			
100	.94	15.62	3.50
75	.88	15.76	3.57
50	.91	15.68	3.53
25	1.04	15.55	3.51

No. 100 and No. 75 is somewhat less than that for fabrics No. 50 and No. 25. Both nitrogen and sulfur content tend to be lower for the fabrics containing large percentages of the reclaimed wool. Others (*3*, *7*) have observed the same general trends.

TABLE 3.—*Physical-test data for stored, dyed flannels, 1942*

Test	Unit of measure	No. 100				No. 75				No. 50				No. 25			
		Warp		Filling		Warp		Filling		Warp		Filling		Warp		Filling	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Strip breaking strength	Pounds	33.7	1.08	28.1	1.29	29.8	1.25	23.8	1.58	24.0	0.72	19.8	0.75	19.2	0.42	17.6	0.77
Bursting strength	Pounds	75.8	1.89			66.2	3.23			58.8	2.41			49.8	2.14		
Strip breaking - strength elongation	Inch	.81	.03	.87	.07	.70	.05	.79	.07	.63	.05	.64	.05	.50	.05	.56	.05
Bursting-strength elongation.	Inch	.28	.08			.28	.08			.25				.40	.13		
Yarns per inch	Number	44.5		39.5		43.4		39.0		43.0		38.7		43.0		38.4	
Fabric thickness	Thousandths of an inch.	37.4	1.03			38.2	.48			37.2	1.06			35.4	.84		
Yarn twist (per inch)	Number	12.54	.46	11.98	.80	11.98	.86	11.60	.67	11.36	.76	11.34	.82	11.68	.86	11.48	.84
Yarn No	Typp	6.34		6.10		6.75		6.46		6.60		6.76		7.83		7.35	

EFFECT OF STORAGE

Control fabrics, stored for a time equivalent to the skirt wearing period, were kept at room temperature and in thoroughly sealed boxes to prevent moth infestation. Several differences in physical-test values between the characteristics of the dyed fabrics before and after storing are noted. Physical-test data for the stored fabrics are given in table 3.

Comparisons of breaking strength indicate a slight increase after storage for all warpwise and fillingwise measurements, although this difference is statistically significant in only two instances, No. 25, warpwise (1-percent level) and No. 50, fillingwise (5-percent level). On the other hand, bursting-strength measurements of the two groups reveal a consistent decrease in mean strength for all stored fabrics, differences which are significant only for fabrics No. 100 and No. 25. Fabric thickness increased upon storage, whereas number of yarns per inch, yarn twist, yarn number, strip elongation, and bursting-strength elongation varied within the range of sampling error.

EFFECT OF STORAGE AND WEAR ON CHEMICAL COMPOSITION OF THE BLENDS

Total ash content for fabrics No. 100 and No. 25 appears to increase after storage (approximately 1 year) and even more so after wear. Fabrics No. 75 and No. 50 show an increase in ash content after the wearing period, but storage effects are inconsistent. A decrease in nitrogen and sulfur is observed following both the storage and the wearing periods. There is some indication that fabric No. 25 is consistently low in both nitrogen and sulfur. Based upon these values, evidences of chemical deterioration are, in general, more pronounced after the wearing period than after the storage period.

EFFECT OF WEAR ON GARMENTS

To interpret the breaking-strength values for both warp and filling directions of the worn materials, the analysis of variance (*6*, *9*) was used. Previous to its calculation, homogeneity of error was determined by Bartlett's method (*14*). Variability of the fillingwise breaking strength within skirt sections was greater than could be explained by errors of sampling. Although heterogeneous, these variable data are the only values for the description of fillingwise strength and since the main effects are of more concern than the interactions, in this analysis of variance these fillingwise-strength data were used. However, the heterogeneous nature of these values must be kept in mind during the interpretation that follows. In all other instances homogeneity of error was found. While this statistical treatment may be considered elaborate because of the limited number of replicates involved, it is hoped that it may prove a guide in future studies of this kind.

The means and standard deviations for warpwise and fillingwise breaking-strength determinations, in pounds, for the three sections

in each of three skirts and for the four fabric blends are given in table 4. The analyses of variance data used in the interpretation of the warpwise and fillingwise breaking strengths are given in table 5.

TABLE 4.—*Means and standard deviations of warpwise and fillingwise breaking-strength determinations for 3 sections in each of 3 skirts made of blended fiber, 1942*

Fabric No. and skirt section	Warp						Filling					
	Skirt No. 1		Skirt No. 2		Skirt No. 3		Skirt No. 1		Skirt No. 2		Skirt No. 3	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
	Lbs.	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*
No. 100:												
Top	33.70	1.16	33.30	1.03	34.80	0.82	29.20	1.78	28.95	1.24	29.35	0.82
Middle	35.15	.41	34.30	.92	35.50	.71	30.25	1.75	30.50	.67	30.10	.88
Bottom	34.30	.79	34.00	.47	35.15	.67	31.80	2.16	30.70	2.00	31.05	1.21
No. 75:												
Top	29.05	.60	28.30	1.08	28.55	1.77	24.05	1.38	25.80	1.03	24.50	1.20
Middle	29.35	.94	28.40	1.35	29.60	.81	25.00	.88	25.05	.76	25.80	.59
Bottom	29.20	.75	28.50	.88	29.30	.89	25.00	.85	25.90	.78	26.05	.80
No. 50:												
Top	24.80	.75	23.60	.91	23.50	.85	21.10	.88	21.35	.82	19.90	.74
Middle	23.80	.72	23.95	.98	23.95	.60	19.95	1.26	21.15	.82	20.35	.58
Bottom	24.65	.94	24.15	.78	23.60	1.02	20.70	1.16	21.85	.67	21.55	.90
No. 25:												
Top	18.80	1.25	19.85	1.27	19.55	.76	15.55	.55	17.40	.46	15.55	.68
Middle	19.85	.71	20.25	.64	19.10	.70	16.60	.70	16.90	1.10	17.05	1.01
Bottom	20.10	.70	20.20	.54	18.40	1.17	16.60	.84	17.75	.64	17.85	1.89

TABLE 5.—*Analysis of variance for warpwise and fillingwise breaking-strength values for the worn material containing various proportions of new and reclaimed wool*

Variation due to—	Degrees of freedom	Warp	Filling
		Mean square	Mean square
Blends	3	3,702.1063**	2,986.9981**
Replications [1]	81	.7005	1.3892
Skirts	2	3.2646	11.7750**
Sections	2	6.3812	41.7250**
Blends × skirts	6	9.4451**	4.2676**
Blends × sections	6	1.6896	4.0259**
Blends × skirts × sections	12	2.0108	2.5370*
Skirts × sections	4	.8677	3.8625*
Error	243	2.1077	1.1458
Total	359		

[1] Replications and interactions of replications and skirts and sections grouped.
* *F* value exceeds the 5-percent level of significance.
** *F* value exceeds the 1-percent level of significance.

From the latter it is seen that the range in warpwise breaking-strength values for the skirts as a whole and for sections of the skirts is insignificant. However, the variation of the fillingwise breaking-strength values among skirts and among the sections of the skirt is highly significant. Evidently variation in individual wearing habits was insufficient to cause noticeable differences among warpwise breaking-strength values for skirts made of the same blend, while these same differences in wearing habits caused a significant difference in the fillingwise strength. The same is true for the warpwise and fillingwise strength values for various sections of the skirts. Because of the greater initial strength of the warp yarns, it is possible that the amount of wear accorded the garments was insufficient to alter the warpwise strength.

The 81 degrees of freedom for the replications given in table 5 include 9 degrees of freedom for replication alone, 18 for replication × skirts, 18 for replication × sections, and 36 for replication × skirts × sections. These have not been separated into their component parts because each represents a controlled portion of the variance due to fabric variation. The resulting mean square for both warpwise and fillingwise strength is nonsignificant. Thus that part of the fabric variation that can be controlled and eliminated in the calculations is small.

The highly significant mean square for fabrics made of blended wool indicates that the average breaking strength for both warpwise and fillingwise directions was significantly different. Use of the *t* test (*14*) shows a consistent and progressively significant decrease in breaking strength of fabric No. 100 through No. 25, warpwise and fillingwise.

Since mean square for interaction of blends × skirts, both warpwise and fillingwise, has been shown to be significantly greater than the mean square for error, it is apparent that, on the average, the relative performance of the blends was not the same for all skirts. The same is true for interaction between blends and sections for the fillingwise breaking strength. However, the fact that the interaction of blends × skirts and blends × sections did not exceed, significantly, the second-order interaction, i. e., interaction among three variables, blends × skirts × sections, indicates that the differential responses in both skirts and sections are not likely to be reproducible.

The statistically significant second-order interaction, blends × skirts × sections for the fillingwise breaking strength shows that the relative performance of these blends in different skirts was not the same in all sections. Since the mean square for blends was greater (1 percent level) than the mean square for both interaction of blends × skirts and blends × sections, it is indicated that blend performance was consistent enough to outweigh the influence of individual skirts and sections. From this we may be sure that these blends would rank in the same order in future service.

In general, an increase in warpwise breaking strength for fabric blends No. 100 and No. 25 was evidenced in comparisons of values for fabrics before wearing with those for the worn material from three sections of the garments. However, in two instances for each blend, the middle skirt section and the bottom skirt section, there was a significant decrease in warpwise breaking strength. Rather consistent fillingwise breaking-strength increases are seen for blends No. 100, 75, and 50. The top skirt section, both warpwise and fillingwise, shows fewer consistent significant differences between the unworn fabric and the material from garments after wear and dry cleaning than do the other two skirt sections. Comparison of warpwise and fillingwise breaking-strength values for stored fabrics with those for material from the worn garments reveals few statistically significant differences.

These fabric-strength increases result, probably, from partial matting or felting of the wool fiber and yarn, in addition to some slight shrinkage (as indicated by yarn count), which accompanies wear and dry cleaning. One thousand hours of wear and seven dry cleanings were insufficient to cause much loss in the breaking strength of the four fabric blends in this study.

Differences in strength between front and back skirt sections after wearing were evidenced in several cases by fairly consistent, positive or negative deviations from the mean breaking-strength values for the top, middle, and bottom skirt sections. It should be noted that the trends mentioned are substantiated only by examination of the data and not by statistical analysis, but the fact that these trends are consistent justifies their consideration. From warpwise and fillingwise breaking-strength values for the garments made of fabrics No. 100 and 25, it can be demonstrated that the top front sections were less strong than the top back, while the bottom back sections were less strong than the front. The bottom front sections of blend No. 50 were consistently lower in breaking strength than the bottom back sections. Values for the middle sections of all garments of all blends showed no constant relationship.

Treating the front and back of the skirts as separate units, fabrics No. 100 and No. 25 gave evidence of an equal number of cases where either front or back strength was superior, while in the majority of cases for blend No. 75 the back exceeded the front in strength. The reverse was true for blend No. 50.

All in all, there is some evidence that, for the blends studied, the top front section of the skirt received more wear than the top back section, while the reverse was true for the bottom sections. Examination of the data reveals no consistent trend as to whether the skirt front or skirt back may be described as giving lower breaking-strength values or as to whether a specific blend reacts consistently toward the imposed wearing conditions as regards skirt sections.

Analysis of variance of the bursting strength of the material from the worn garments (table 6) indicates a highly significant difference between the fabric blends. Apparently little variation was due to individual wear habits or to possible interaction between fabrics and skirts. It should be noted that by not grouping mean square of replication and replication × individuals, variation due to replication alone is significant at the 5-percent level, suggesting either a difference in fabric bursting strength in various parts of the skirt or inadequate sampling. The latter inference is not wholly unexpected because of the sampling procedure arbitrarily chosen.

TABLE 6.—*Analysis of variance of bursting-strength determinations of the worn garments containing various proportions of new and reclaimed wool*

Variation due to—	Degrees of freedom	Mean square
Blends	3	3,527.7806**
Replications [1]	27	7.6782
Skirts	2	6.8812
Blends × skirts	6	9.9368
Error	81	5.5714
Total	119	

[1] Replications and replications × skirts grouped.
** = *F* value exceeds the 1-percent level of significance.

One thousand hours of wear plus seven dry cleanings resulted in a marked loss in bursting strength for fabrics from the three garments made of 100 percent new wool (table 7). The loss for fabrics No. 75 and 50 was nonsignificant, while only one garment made of fabric No. 25 showed a real loss in fabric bursting strength. However, there still exists the marked difference between the four blends after wear. Actual bursting-strength losses due to wear and dry cleaning range from 5.15 pounds for skirt, No. 1 and No. 2 of blend No. 100 to 1.15 pounds for skirt No. 2 of blend No. 25. It is interesting to note that the average loss in pounds for all blends decreases progressively, 5.03, 2.97, 2.65, 2.60 for fabrics No. 100 to No. 25, respectively.

TABLE 7.—*Yarn-count, thickness, bursting-strength, and bursting-elongation values for the worn materials containing various proportions of new and reclaimed wool, 1942*

Fabric and skirt identification	Yarn count		Thickness		Bursting strength		Bursting elongation	
	Warp	Filling	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
	Number	*Number*	*1/1,000 in.*	*1/1,000 in.*	*Pounds*	*Pounds*	*Pound*	*Pound*
No. 100:								
Skirt No. 1	44.9	40.7	37.55	1.01	75.95	2.44	0.25	0
Skirt No. 2	44.0	40.6	37.95	.55	75.95	2.75	.25	0
Skirt No. 3	45.1	40.6	38.05	1.09	76.30	3.50	.25	0
No. 75:								
Skirt No. 1	44.0	39.6	38.50	1.62	66.25	2.68	.25	0
Skirt No. 2	43.8	39.4	38.10	.70	66.25	2.34	.25	0
Skirt No. 3	44.5	39.7	39.20	.92	67.30	2.45	.25	0
No. 50:								
Skirt No. 1	43.7	39.4	37.15	1.55	59.05	2.06	.25	0
Skirt No. 2	43.5	39.1	37.25	1.11	59.05	2.34	.25	0
Skirt No. 3	43.4	39.3	36.40	.88	58.15	1.73	.25	0
No. 25:								
Skirt No. 1	42.8	39.4	35.75	.98	51.25	2.71	.25	0
Skirt No. 2	42.8	39.0	35.55	.86	52.20	1.90	.25	0
Skirt No. 3	43.0	39.2	35.00	.97	48.80	2.24	.25	0

Bursting elongation after wear was the same for all fabric blends. The small decrease evidenced between bursting elongation of dyed fabrics before and after wearing was not statistically significant.

As may be seen from tables 8 and 9, the highly significant mean square for blends, as shown by an analysis of variance of both warpwise and fillingwise strip-elongation determinations, indicates real differences between the fabric elongation for the four blends. Fabric elongation differed in various skirt sections, both warpwise and fillingwise, although variation in elongation in skirts of the same blend was significant only in the filling direction. Since for both warp and filling directions, the interaction of blends $\times$ skirts and blends $\times$ sections is significant (1-percent level), fabric elongation variation for each blend is not the same for all three skirts and all three sections. In general, these first-order interactions exceed the second-order interaction, blends $\times$ skirts $\times$ sections, only at the 5-percent level, thereby allowing controversial interpretation as to the significance of reproducibility of results in this case.

The skirt measurements taken before and after each dry cleaning reveal that the skirt dimensions, with very few exceptions, either increased or remained the same throughout the wearing period. It appears that wear tended to offset any permanent shrinkage which might be caused by dry cleaning.

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TABLE 8.—*Means and standard deviations of warpwise and fillingwise fabric-elongation determinations in inches for 3 sections in each of 3 skirts made of blended fiber, 1942*

Fabric No. and skirt section	Warp						Filling					
	Skirt No. 1		Skirt No. 2		Skirt No. 3		Skirt No. 1		Skirt No. 2		Skirt No. 3	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
No. 100:												
Top	0.81	0.06	0.80	0.05	0.84	0.07	0.81	0.10	0.80	0.07	0.87	0.07
Middle	.86	.05	.84	.07	.88	.04	.92	.06	.87	.05	.92	.06
Bottom	.94	.05	.89	.06	1.00	.08	1.01	.06	.93	.08	.98	.10
No. 75:												
Top	.72	.06	.72	.06	.73	.07	.70	.10	.80	.07	.81	.06
Middle	.78	.04	.75	.05	.79	.06	.81	.03	.79	.03	.87	.05
Bottom	.81	.06	.85	.08	.83	.07	.81	.06	.85	.05	.93	.05
No. 50:												
Top	.67	.07	.62	.06	.65	.07	.72	.03	.70	.05	.67	.05
Middle	.64	.05	.65	.05	.62	.04	.67	.05	.71	.03	.72	.06
Bottom	.71	.03	.69	.03	.69	.06	.73	.05	.75	.07	.70	.07
No. 25:												
Top	.51	.06	.53	.07	.51	.03	.54	.05	.59	.06	.55	.05
Middle	.52	.04	.55	.05	.50	.05	.59	.06	.63	.07	.61	.03
Bottom	.56	.05	.55	.05	.53	.05	.64	.07	.59	.06	.62	.06

TABLE 9.—*Analysis of variance of warpwise and fillingwise fabric elongation for the worn materials containing various proportions of new and reclaimed wool*

Variation due to—	Degrees of freedom	Warp	Filling
		Mean square	Mean square
Blends	3	1.9883**	1.5956**
Replications [1]	81	.0037	.0043
Skirts	2	.0037	.0220**
Sections	2	.1952**	.2054**
Blends × skirts	6	.0130**	.0273**
Blends × sections	6	.0177**	.0200**
Blends × skirts × sections	12	.0038	.0079*
Skirts × sections	4	.0009	.0070
Error	243	.0030	.0036
Total	359		

[1] Replications and interactions of replications and skirts and sections grouped.
*=F value exceeds the 5-percent level of significance.
**=F value exceeds the 1-percent level of significance.

Variations in yarn count among the unworn dyed fabrics and fabrics from the 12 skirts differed no more than 1 to 1½ yarns per inch for either warp or filling directions, indicating relatively stable yarn count regardless of the imposed wearing conditions, as would be expected.

At the end of the total wear period materials from all garments had increased in thickness, although not significantly more than the increase observed during the storage period. Fabric No. 25 continued to be the thinnest fabric blend.

SUMMARY

Four flannel fabrics containing various proportions of new wool of known history and high-quality sweater clips were made into 12 four-gore skirts and issued to women students at South Dakota State

College for a wearing period including 1,000 hours of wear and 7 dry cleanings.

Physical and chemical tests were made on the blended fabrics after they were received from the dyers, after the total wearing period, and after a storage period equivalent in time to the skirt wearing period. It should be emphasized that the data and interpretation reported herein pertain only to fabrics made of the particular quality of new and reclaimed wool fiber used in this study.

Percentage loss, based on the strength of the 100 percent new-wool fabric, in warpwise breaking strength which resulted from the blending of new and reclaimed wool used in this study ranges from approximately 12 percent for fabric No. 75 to 46 percent for No. 25. Fillingwise breaking-strength and bursting-strength values also reveal significant strength decreases throughout the series from fabric No. 100 to No. 25.

Increases in fabric thickness and in certain breaking strength determinations and decreases in certain bursting-strength determinations were observed when comparing values for stored material with those for the material before storing. Other physical measurements for the stored materials varied within the limits of sampling error.

Both nitrogen and sulfur content, calculated on a moisture-free basis, tend to decrease for the dyed fabrics containing large percentages of reclaimed wool; however, this decrease does not hold consistently for the stored and worn blended fabrics. A decrease in nitrogen and sulfur was found following the storage and the wearing periods as compared to the corresponding newly dyed fabrics. The total ash content for all blends increased after the wearing periods. Evidences of chemical deterioration appear to be more pronounced after the wearing period than after storage.

Analysis of variance of breaking-strength values for the skirt fabrics gave evidence that variations in individual wear habits were not sufficient to cause noticeable differences among warpwise breaking-strength values for fabrics made of the same blend, while a differential influence of wear on the filling yarns was noted. The relative performance of the blends was not the same for all skirts or for all skirt sections. However, the differential responses for both skirts and sections are not likely to be reproducible. It is demonstrated that blend performance was consistent enough to outweigh the influence of individual skirts or sections. One thousand hours of wear and seven dry cleanings were insufficient to cause much loss in breaking strength of the four fabric blends used in this study, but actual bursting-strength losses due to wear and dry cleaning ranged from 5.15 to 1.15 pounds. Fabric elongation, as measured by both warpwise and fillingwise strip-elongation determinations on the worn fabrics, decreased significantly from fabric No. 100 to No. 25.

The statement that wool fibers reclaimed from unused knit material are not damaged sufficiently "to seriously diminish their original, natural intrinsic protective and service qualities" (*1*) is not supported by these findings.

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DETERMINING NET RAINFALL UNDER A CONIFER FOREST [1]

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INTRODUCTION

It is generally accepted that considerable quantities of rainfall and snowfall are intercepted by tree crowns in the forest. Where water supply or flood control is a crucial factor in regional economy, however, those responsible for management of watersheds need to know more exactly how much of the total precipitation reaches the ground beneath any forest canopy, and to what extent this quantity is augmented by removal of trees in timber-cutting operations. In research on methods of watershed management, measurement of unintercepted or "net" precipitation is indispensable. Since controlling conditions may vary considerably within a single forest-type zone in any given region, this measurement presents a rather involved problem in sampling.

Interception of precipitation by trees has been studied by a number of investigators during the past 60 years and more, but practically all of this research has been based on measurements referred to individual trees. Estimates of effective or net precipitation per acre have been obtained only by conversion. Results of the earlier work on interception, especially that done in Europe, have been summarized by Zon (*11*) [4] and Horton (*2*).

Among more recent results are those detailed by Horton (*2*), who studied interception by open-grown and hedge trees of various species in New York State. There he found that the initial storage capacities of individual trees ranged from 0.02 to 0.07 inch of precipitation. Pines and hemlock stood midway in the scale, which included species of willow, basswood, maple, oak, horsechestnut, beech, apple, ash, elm, and hickory. Net rainfall under the trees ranged from none, for observed storms below 0.07 inch, to about 75 percent of the total in large storms of long duration.

Other recent studies include those by Beall (*1*) and Lunt (*4*), and one by Kittredge et al. (*3*) in a young plantation of Canary pine in California. Kittredge found that interception by tree crowns ranged from 17 to 28 percent of the season's precipitation, with an initial storage of 0.02 to 0.04 inch per storm.

In 1938 and 1939 Wicht (*7*) in South Africa attempted to make direct measurements of net precipitation under a forest canopy in a

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[3] Maintained by the Forest Service, U. S. Department of Agriculture, at Fort Collins, Colo., in cooperation with Colorado State College of Agriculture and Mechanic Arts.
[4] Italic numbers in parentheses refer to Literature Cited, p. 512.

stand of gray poplar (*Populus canescens*). Wicht employed four rain gages and, by moving the cans from place to place, sampled rainfall at a total of 20 sites within his sample plot. Sampling errors were computed from records for rain gages which were located not at random but mechanically along the sides of a 50-foot square. "Gross" rainfall was measured by means of a single gage in the open, 350 feet from the sample plot.

In its watershed management studies in the lodgepole pine type in Colorado, the Rocky Mountain Forest and Range Experiment Station had need for a similarly direct means of measuring the influence of a forest canopy of mature timber on net precipitation. Accordingly, the writer (*9*) in 1938–40 made a detailed study in this type and class of timber of the effect of timber cutting on net rainfall and flow of rainfall along tree stems, excluding the interception of snow, which was the subject of a separate investigation (*8*). The results showed that stem flow was negligible and that cutting in general augmented materially the net rainfall; but the data on influence of cutting intensity were somewhat inconclusive. Minor discrepancies in the effects of treatment as measured in that study were thought to be due to errors of sampling of interception in a forest. For this reason, and because earlier studies of rainfall interception have shown deficiencies in experimental method, the experiment was redesigned and repeated.

The objectives of the second study, conducted in the summer of 1941 and confined to rainfall only, were to provide a check on earlier results and, by means of an improved experimental design, to measure more accurately the influence of cutting intensity upon net rainfall; also, to demonstrate that an efficient design makes it possible to obtain accurate results with a minimum of work and expenditure for equipment. In view of these objectives, the results and conclusions recorded here quite naturally and unavoidably stress method and design equally with the biological and physical aspects of the study.

EXPERIMENTAL SITE AND PLOTS

Together with related investigations in watershed management, this study was conducted on the Fraser Experimental Forest, at the headwaters of the Colorado River near Fraser, Colo. The type is mature lodgepole pine *(Pinus contorta latifolia)*, the average elevation 9,300 feet. Weather conditions, topography, and forest cover are typical of the general zone. The plots include considerable variation in slope, exposure, and timber-stand characteristics. The greater part of the annual precipitation on the area occurs as snow. Rainfall during the snow-free period (June through September) ranges from about 3 to more than 10 inches. Individual rainstorms are ordinarily gentle and light, averaging about 0.25 inch and seldom exceeding 1 inch in depth.

The experiment was conducted on 20 plots, each 5 acres in area, grouped in 4 blocks of 5 plots each. In each block, 4 intensities of cutting treatment had been applied in 1940, and the fifth plot was uncut (fig. 1). The 4 kinds of treatment, assigned to as many plots in each group at random, had left commercial reserve stands of 0, 2,000, 4,000, and 6,000 board feet per acre, respectively. By "commercial" reserve stand is meant residual merchantable trees more than 9.6 inches in breast-height diameter. Cutting was restricted

to trees above that size; thus even the "clear-cut" plots contained residual stands of small and unmerchantable trees. As a minor treatment, on half of each treated plot the undesirable trees were removed by cutting. The other plots were given no stand improvement.

SOURCES OF VARIATION AND METHODS OF SAMPLING

The considerable variation characteristic of net rainfall under a forest canopy may be divided into two general classes, each having several sources. The first class includes variations common to all

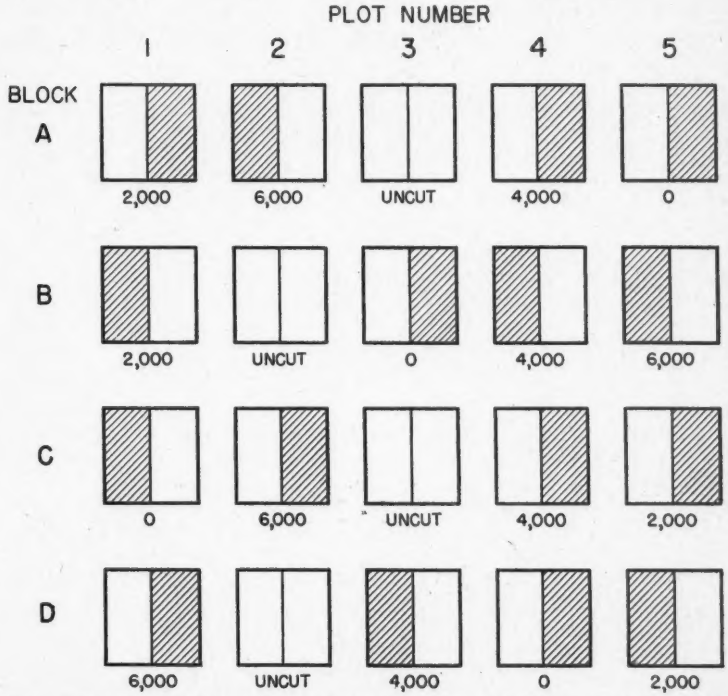

FIGURE 1.—Distribution of treatments, in four randomized blocks. Figures under plot diagrams signify commercial reserve stand per acre in board feet. Hatching signifies timber-stand improvement.

observations of net rainfall on a given area or a given plot; the second, variations among individual observations within the area or plot.

In the present experiment the average net rainfall on any half-plot may deviate from the "true" average—for all possible like-treated half-plots in the universe of mature lodgepole pine—because of local effects of altitude, exposure, and related factors on gross rainfall. It may differ also from averages for other half-plots because of variations in character of the forest from place to place; the various plots and half-plots may not have been alike before treatment, and each treatment may not have left the same residual stand on all the half-

plots to which it was applied. Variances (squared standard deviations) due to these sources of variation represent the true interaction of treatment with block—the differential in response of net rainfall to treatment among tne several blocks. This interaction affords a strictly unbiased estimate of experimental error only if each block has been located at random in the universe of mature lodgepole pine and if variations among plots in the intensity of a given treatment represent a random sample of all possible variations in that treatment. In practice such conditions can seldom be quite fulfilled; ordinarily, in any experiment such as this, areal limitations preclude random sampling of the universe under consideration. Then the estimated experimental errors are correspondingly limited in general utility, and judgment and conservatism must be used in extending results to other areas.

Sources of variations in the second class are commonly called sampling errors. Since it is impracticable to measure every possible variation in net rainfall on each half-plot, an attempt must be made by sampling to obtain a reasonably accurate estimate of the true average net rainfall. The extent to which the average of the sample will deviate from the true average depends upon the number and distribution of samples and upon the magnitude of variations in net rainfall within the half-plot. These variations (aside from personal and instrumental errors) may arise from three general sources: (1) Variations in forest cover density from place to place within the plot; (2) variations in net rainfall at a single sampling spot, for storms of the same size; and (3) variations in gross rainfall from storm to storm and from place to place within the plot.

The magnitude of each sampling observation will deviate more or less from the true average of net rainfall according to the sizes and directions of the variations arising from these sources. If all the components of variation are random and independent in character, the mean value of each or their joint value will approach zero as the number of plots within the universe and the number of samples taken within a plot increase. The variations themselves may be random and compensating; their squares, on the other hand, are all positive, and the variances due to all components of variation are added together to form the variance for experimental error.

Assuming that all the variations in both classes are random and independent in the probability sense, we may express the magnitude of any single observation by the equation.

$$x_{ij}=P+a+b_1+b_2+b_3, \tag{I}$$

in which x_{ij} is any single sample of net rainfall at sampling place j within the half-plot i; P is the true average net rainfall for any single treatment; a is a component of random variation arising from all sources common to a single plot or half-plot; and b_1, b_2, and b_3 are the variations of the second class arising from the three general sources, in the order listed above. The true value P cannot be determined; it is possible, however, to estimate the variance of sample observations around the true value by employing the familiar formula (with extensions to include two or more categories of variation)

$$s^2=\frac{S(x-\bar{x})^2}{n-1}, \tag{II}$$

in which s^2 is the estimated variance, S is a sum, x is any sample observation, $\bar{x}$ is the average of all observations, and n is the number of observations. Then, in terms of variances, equation (I) may be expressed as

$$s_T^2 = s_a^2 + s_{b_1}^2 + s_{b_2}^2 + s_{b_3}^2, \qquad \text{(III)}$$

in which s_T^2 is the variance of a single sampling observation for any one treatment and s_a^2 etc. are variances due to the four components of variation mentioned above. In subsequent discussion these variances will be identified only by their subscripts (capitalized), as "A" for "s_a^2."

If the largest practical number of uniform blocks has been established and the treatments carefully applied, the A component is unchangeable in the magnitude of its influence upon the average net rainfall under each treatment. Since, however, the error variance of any average decreases directly with the number of observations, the influence of the B components may be minimized by taking a maximum number of samples of net and gross rainfall within each half-plot; and B_3 may be largely removed by adjusting net rainfall to values expected for the average gross rainfall of all samples. In addition it is possible, by proper design of the sampling procedure, to evaluate the individual influence of each B component.

For the present study, the objectives of sampling were to obtain treatment averages accurate within approximately 5 percent, and to obtain an unbiased estimate of each component of error.

Very rough estimates of sampling errors derived from earlier studies indicated that rainfall should be sampled at not less than 10 places on each 2½-acre half-plot. According to past procedure 400 pairs of rain gages would be required, one member of each pair to be used for measuring net rainfall and the other for measuring gross rainfall. One season's records would then include roughly 10,000 to 12,000 pairs of observations. Since this number seemed excessive, and since earlier studies had indicated that the errors due to variations in storm size could be largely removed by regression, it was decided to simplify sampling by partial confounding of the B_3 component with the two other components of sampling error within each half-plot. Accordingly 12 rain-gage locations were selected at random for the measurement of net rainfall on each half-plot. Then one pair of 8-inch standard rain gages was assigned to each half-plot. The "net" gage was placed at one of the 12 selected sites, then the gage to be used for measuring gross rainfall was placed in the center of the nearest available opening of a size large enough to free the records from interception effects—at least 30 feet in diameter. After each storm the "net" rain gage was moved to a new site, and the "gross" gage placed in the nearest suitable opening. Thus a series of 12 storms gave 1 complete circuit of the locations on each half-plot. For the succeeding 12 storms, the same locations were used in newly randomized sequence. Thus after 24 storms 2 pairs of readings were available for each of 12 locations on each of 40 half-plots—a total of 960 observations.

Depth of rainfall was recorded in inches. Since the locations for measurement of net rainfall were randomized over each half-plot, the resulting data expressed net and gross rainfall directly in inches per unit of plot area.

METHODS OF ANALYSIS

The study was so designed that analysis of variance and covariance (*5*, *6*) could be applied. The null hypothesis to be tested was that differences in net rainfall associated with the major and minor treatments were no greater than variations, due to uncontrolled causes, which might occur by chance. In simplified terms, the analysis partitioned the total variance (squared standard deviation) of the study into two general classes, the variances between and within groups of data (see table 2). The former, measuring controlled variation, are the variances between major treatments (1), between blocks (2), and between minor treatments (3), and the interaction of major and minor treatments (1×3). The "within" variances, measuring uncontrolled variation, are composed of the several mean squares which form the experimental errors for testing treatment effects. The interaction of major treatment with block forms the experimental error appropriate for testing major treatments. The minor-treatment error includes three variances—the interaction of minor treatment with block (2×3), the triple interaction (1×2×3), and the variance between the halves (both untreated) of each uncut plot. Each of the two experimental errors is the sum of variances arising from all sources of sampling error.

In order to minimize sampling errors due to variation in gross rainfall (B_3), all the variances mentioned above were adjusted by regressions of net rainfall on gross. As a result, each of the two other components of sampling error within plots (B_1 and B_2) has confounded in it the errors of estimate of the regression of net rainfall on gross. In subsequent discussions, the variances expressed by B_1 and B_2 will be understood to include this residual portion of B_3.

As usual, the procedure in analysis of covariance involved simply the computation of average net rainfall per plot and per treatment, adjusted to the average value for gross rainfall, and, for tests of significance, the calculation of mean squares for all components of variation, adjusted by the "error" regressions of net rainfall on gross. Individual storm observations as well as half-plot averages were used in this analysis, in order to provide estimates of sampling errors.

On the assumption that each of the several components of variation contributed a significant amount to experimental error, the valuation of these components for the major-treatment error in the present study may be laid out as follows:

Mean square (errors of estimate):	*Components*
Within rain-gage locations	B_2(IV)
Between locations within half-plots	$2B_1+B_2$ (V)
Interaction of block and major treatment	$48A+2B_1+B_2$ (VI)

Similar formulas are applicable to the minor treatment. The formula for interaction is simply III modified to fit the mean squares computed in the variance analysis. The "between locations" mean square does not contain the variance A, which is common to all observations within a half-plot, and the "within locations" mean square contains neither A nor B_1, which is common to all observations at a single location.

Each component is a squared standard deviation, and the numerical coefficient of each is the number of observations (k) making up each subclass sum from which the mean squares were computed (*5;*

6, sections 10.13 and 17.8). Thus the "within sites" term is a variance of individual observations around the mean of two readings, k being 1; the major-treatment interaction, on the other hand, is a mean square which is 48 times the corresponding variance of whole-plot averages (each average based on observations of 2 storms in each of 12 locations on 2 half-plots—48 observations altogether).

Since the experiment was designed to provide numerical values for each of the above-mentioned mean squares, an estimate of each component of error could be obtained by successive solutions of expressions V and VI (*10*).

RESULTS

When adjusted to the average gross rainfall [5] for all plots, the average net rainfall per storm indicated a strong and consistent effect of the major treatment (table 1). Considering the half-plots which were not subjected to stand improvement cutting, only 68.4 percent of the gross precipitation reached the ground on the uncut plots, but 90.4 percent did so on the clear-cut plots. Values for the other major treatments approximated a straight line between the two extremes. Figures from earlier experiments (*9*) agreed well with these, except that the linear relation of net rainfall to treatment was obscured by experimental error.

In striking contrast with the pronounced effect of the major treatments, influence of timber-stand improvement was apparently lacking. The advantage shown by the "improved" half-plots over the unimproved in net rainfall amounted to only 2.0 percent of the gross rainfall. The nonsignificance of this quantity is demonstrated by two facts: In the 6,000-board-feet treatment, net rainfall was actually greater on the unimproved half-plots than on the improved; and the uncut half-plots showed as much variation among themselves as occurred between the improved and unimproved cut-over half-plots.

TABLE 1.—*Average net rainfall per storm, adjusted to average gross rainfall*[1]

Stand per acre after major treatment (board feet)	Improved half-plots		Unimproved half-plots		Average	
	Inches	*Percent*	*Inches*	*Percent*	*Inches*	*Percent*
11,890 [2]	0.175	70.0	0.171	68.4	0.173	69.2
6,000	.199	79.6	.205	82.0	.202	80.8
4,000	.216	86.4	.209	83.6	.213	85.2
2,000	.220	88.0	.211	84.4	.216	86.4
0	.238	95.2	.226	90.4	.232	92.8
Average	.210	84.0	.204	81.6	.207	82.8
Average for treated half-plots	.218	87.2	.213	85.2		

[1] Net rainfall has been adjusted to an average gross rainfall of 0.250 inch. This average is the base of the percentages.
[2] No major treatment; neither half-plot was improved.

The indications in table 1 are supported by the analysis of variance and covariance (table 2). The differences associated with major treatments were found to be significantly greater than the chance variations expressed by experimental error ($F = .0756 \div 0.00527 = 14.3$; $p. = < 0.01$). Further, each individual treatment resulted in net rainfall significantly greater than that occurring under virgin conditions,

[5] The average gross rainfall was 0.25 inch per storm; a total of 5.99 inches of rain was recorded in 24 storms between May 22 and September 3, 1941.

TABLE 2.—*Analysis of variance and covariance, net rainfall per storm*

Source of variation	Net rainfall		r [2]	Errors of estimate [1]	
	Degrees of freedom	Mean square		Degrees of freedom	Mean square
Total	959	0.0351	0.8825	958	
Between means of:					
(1) Major treatments	4	.1291**		4	0.0756**
(2) Blocks	3	.0247		3	.0234*
(3) Minor treatments	1	.0069		1	.0068
Interactions:					
(1 x 2) [3]	12	.0087	.4450	11	.00527
(1 x 3)	3	.0055		3	.0051
(2 x 3), (1 x 2 x 3), and within uncut plots	[3] 16	.0056	.0460	15	.0060
Within half-plots (sampling error):					
(B^1) Between locations	440	.0359	.8776	439	.00441
(B^2) Between storms within locations	480	.0356		475	.00258

Regression formulas:
In interaction 1×2: $E=0.9549\,x-0.0313$; $r=+0.667$.*
In sampling error B_1: $E=0.9667\,x-0.0342$; $r=+0.937$.**
In sampling error B_2: Uncut: $E=0.8046\,x-0.0290$; $r=+0.946$.**
6,000 board feet: $E=0.8677\,x-0.0149$; $r=+0.948$.**
4,000 board feet: $E=0.9055\,x-0.0131$; $r=+0.956$.**
2,000 board feet: $E=0.8933\,x-0.0074$; $r=+0.966$.**
0 board feet: $E=0.9897\,x-0.0153$; $r=+0.993$.**
The B_2 regressions differ significantly from each other ($F=7.236$).
[1] Around "error" regressions of net rainfall on gross rainfall.
[2] Experimental error for major treatment.
[3] Experimental error for minor treatment.

as can be shown by analysis of the single degrees of freedom associated with the treatments (for example, for the 6,000-board-foot treatment $F=13.8$). It is improbable that the magnitude of apparent effects of major treatments was appreciably influenced by the minor treatment, since the interaction of major and minor treatments was no greater than its experimental error.

The mean square expressing effect of minor treatment on net rainfall was only slightly larger than the error mean square.

The results of tests of treatment effects are presented in table 2 in the column "errors of estimate," which shows all effects adjusted to the average size of storm for all plots. The procedure of adjustment materially augmented experimental precision in comparing the major treatments; this is shown by the reduction in size of the error mean square (0.00527 for adjusted as compared with 0.0087 for unadjusted averages). It is sounder in principle than the more common recourse of analyzing net rainfall or interception as a percent of gross rainfall.

Aside from the tests of treatment effects, table 2 presents regression statistics which cast additional light on the influence of major treatments upon net rainfall. Of the numerous "error" regressions within treatments, only those computed for sampling error B_2 varied significantly among the five major treatments. Accordingly an individual regression formula was computed for each treatment; and the B_2 mean square in table 2 is the average of the errors of estimate for the five regressions. By equating each of these formulas to zero, the initial crown storage per acre was computed (with some error) for each major treatment. According to the computations about 0.036 inch of rain had to fall on the uncut stands before amy rainfall penetrated the forest canopy. The corresponding figures for the four major treatments, in ascending order of treatment intensity, are 0.017, 0.014, 0.008, and 0.015 inch. By use of these formulas net rainfall on these particular plots can be computed with considerable accuracy

for any given storm value. In a storm of 0.60 inch, for example, the net rainfall on the uncut plots would be about 0.45 inch; on the "clear-cut" plots, about 0.58 inch. The error of these predictions may be estimated by use of the formula

$$V_E=\frac{V_{y.x}}{n}+(X-\bar{x})^2\left(\frac{V_{y.x}}{Sx^2}\right),$$

in which V_E is the variance of the predicted value for net rainfall; $V_{y.x}$ is the mean square for errors of estimate (B_2); X is the gross rainfall from which net rainfall is estimated (0.60 inch); $\bar{x}$ is the mean gross rainfall on which the regression was based; and Sx^2 is the sum of squares for x in the regression data. For the uncut plots in a storm of 0.60 inch,

$$V_E=\frac{0.00258}{192}+(0.60-0.250)^2\left(\frac{0.00258}{4.4656}\right)=$$

$$0.000013+(0.1225)(0.000578)=0.000084.$$

The corresponding standard error is ± 0.009 inch, about 2.0 percent of the estimated net rainfall of 0.45 inch. Similarly, the error of the computed "initial storage" on the commercially clear-cut areas was found to be ± 0.0057 inch; thus the deviation of the computed value (0.015 inch) from the strong trend shown by the other treatments is probably due to chance.

Examination of the mean squares for the several components of error reveals that neither experimental error greatly exceeds the desired limit, 5 percent of the average net rainfall. For major treatments, the standard error of treatment averages is ± 0.0052 inch $\left(\sqrt{\frac{0.00527}{192}}\right)$, or about 3.0 percent of the lowest average value per storm for a single treatment (that for uncut plots, 0.173 inch). For minor treatments, the corresponding standard error is 0.0035 inch, or 1.7 percent of the average value per storm (0.204 inch) for the 20 unimproved half-plots.

Since the error of the major-treatment averages exceeded 5 percent (3.0 percent times t at the 0.05 level for 11 degrees of freedom = about 6.6 percent), it may be illuminating to analyze the mean square for the experimental error of major treatments; that is, to determine the magnitudes of its several components and estimate in what way experimental error can most efficiently be brought down to the desired limits. In the present study this analysis was somewhat academic, since the major treatments were shown to have very significant effects and the minor treatment to exert no appreciable influence; however, exposition of the method and evaluation of error components may assist in preparation of efficient experimental designs for future studies.

As has been pointed out (expression VI), the interaction of block and major treatment has three general components of error; its mean square may be expressed as $48A+2B_1+B_2$. Parenthetically, then, the variance of treatment averages may be expressed by the equation

$$V=\frac{\text{mean square}}{192}=\frac{MS}{48\times 4}=\frac{A+B_1/_{24}+B_2/_{48}}{4},$$

since the mean square for single plots is 48 times the variance of plot means and each treatment average is based on 4 plots. From available data numerical estimates of each of these three components can now be computed. In table 2, the adjusted mean square[6] for variation "between locations within half-plots" (0.00441) contains variances due to the random error of measurements at a single location ($B_2=0.00258$) and due purely to variation in net rainfall from place to place within a half-plot ($2B_1$, since the average for each location is based on two storm observations). Thus

$$0.00441=2B_1+0.00258, \text{ and}$$
$$B_1=0.00092$$

Then the mean square for experimental error may be analyzed as follows:

$$0.00527=48A+0.00183+0.00258;$$
$$48A=0.00086, \text{ and}$$
$$A=0.000018.$$

Now it can readily be seen, by comparing the magnitudes of B_2, $2B_1$, and $48A$, that the interaction mean square is composed chiefly of sampling errors, which in turn consist chiefly of variations between measurements at a single site. Since the given arrangement of observations failed to yield averages accurate within 5 percent, it is desirable to make one or more of these components of error smaller if possible. The A component is so small that further reduction by the use of additional plots would seem unnecessary; and the B_3 component (due to storm size) has been reduced as far as possible by the regressions of net rainfall on gross. Either of the two other B components can be reduced, however, by increasing the number of locations sampled or the number of storm observations at each location.

Assuming that the several components have been estimated with reasonable accuracy, it is not difficult to work out the arrangement of storm observations which is likely to reduce most efficiently the error of treatment averages. The first step is to ascertain the most efficient arrangement of samples; that is, to estimate what number of observations at each location will provide maximum accuracy with least work. For this purpose, use may be made of the formula $k^2=\frac{c(B_2)}{(B_1)}$, in which k is the optimum number of samples to be taken at a single location and c is the number of samples which can be taken at each place in the time required to move to a new location and set up the rain gage for a new reading. In the present study c may be taken as unity, because it is believed necessary to move gages after each storm. Then,

$$k^2=\frac{0.00258}{0.00092}=2.8043, \text{ and } k=1.67,$$

or, in round numbers, two observations at each location. Thus, in order to reduce the error of treatment averages to the desired limits with a minimum of work, it is desirable to sample additional locations

[6] Unadjusted mean squares could not be used in this analysis. Since storm size was assigned at random only to individual samples within half-plots, the unadjusted mean squares for sampling errors are much larger than the corresponding mean squares for the two experimental errors, to which storm size was not randomly apportioned.

rather than take more samples at each of the 24 places within each whole plot.

Now the number of locations required to provide the desired standard error (about ± 0.0043 inch) may be estimated by solving the interaction formula equated to k_1, the desired number of locations:

$$k_1 = \frac{B_1 + B_{2/2}}{4V_x - A}.$$

In this case

$$k_1 = \frac{0.00092 + 0.00129}{0.000074 - 0.000018} = 39.46,$$

or about 40 locations.

By another solution of the same formula it is possible to demonstrate the greatly increased sampling efficiency obtained by moving gages between storms instead of using gages left in the same place for an equal number of storms. If 40 storms were measured with each pair of gages, for example, about 340 pairs of gages at fixed locations (at least 17 pairs per whole plot) would probably be required for the experiment in order to provide treatment averages accurate within 5 percent; or, if 24 storms were measured with each pair, well over 200 pairs of gages at fixed locations would be necessary to attain the present accuracy of 6.6 percent. In the first of these two examples, the calculation was as follows:

$$k_1 = \frac{0.00092 = 0.00258/40}{0.000074 - 0.000018} = \frac{0.000984}{0.000056} = 17.5,$$

or, in round numbers, 17 pairs of gages per whole plot.

The relative efficiency of the recommended sampling method is obvious when the labor and equipment required by the alternate procedure are considered. With rain gages at fixed locations, the necessary investment in gages alone would be prohibitive for most studies—about $2,000 (at $3 per instrument) as compared with $240 for the 80 gages employed in the present experiment. The labor of reading 680 rain gages would greatly exceed that of reading and moving 80 gages; and the effort required for compiling and analyzing 27,000 individual storm observations would hardly be pleasant to contemplate.

SUMMARY AND CONCLUSIONS

Analysis of the results of the experiments described here reveals a significant relation between degree of timber cutting and amount of rainfall reaching the ground. Cutting mature lodgepole pine to a commercial reserve stand of 6,000 board feet or less per acre will cause significant increases in net rainfall. The event of increase of tree reproduction and other vegetation will of course alter this relation. Net rainfall appears to vary in linear relation to the intensity of cutting. The analysis indicates, however, that removal of undesirable trees, that is, the described timber-stand improvement work, resulted in no appreciable increase in net rainfall. Presumably variations in stand density that are not readily measurable obscure the effect of improvement cuttings.

Regarding the experimental design and the statistical method

employed in the study described here, it is evident (1) that the design is satisfactory for measuring at least major treatment effects, and is very much more efficient than previously used methods of sampling; and (2) that in any sampling of rainfall interception, maximum efficiency can be expected to result from taking two pairs of storm observations at each of a number of randomized sampling locations. The latter conclusion should, of course, be verified by actual trial in any new experiment.

For new studies it is recommended that sampling of net rainfall be designed to provide randomized measurements at a maximum number of locations with the least practicable number of storm observations—usually two—at each site. In any experiment measurements should be taken in two or more seasons, so as to obtain an estimate of the interaction of treatment with season. Unless the number of storms occurring in a single season makes it possible to sample rainfall at a number of locations sufficient to minimize sampling error, it may be desirable to use a new set of randomized sites for each season's work. With this modification and any others needed to fit local conditions or different sampling problems, the experimental design employed should prove satisfactory in other forest types. The general principles and procedure in the analysis of sampling errors may be applied also in other kinds of sampling experiments.

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